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SIMULATION OF TRAFFIC AT A TWO-WAY STOP INTERSECTION

A THESIS

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by

James Nelson Thomasson, Jr.

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TWO-WAY STOP INTERSECTION

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Chairman

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

List of Figures (Cont.)

List of Figures (Cont.)

SUMMARY

The objective of this research was to simulate on a digital computer a street intersection controlled by two-way stop signs and, by use of this simulation model, to study the operational characteristics of the intersection.

The research included an empirical study of driver behavior at three intersections in metropolitan Atlanta, Georgia. Results of this study served as inputs to the computer model. The program was written in ALGOL EXTENDED 60 language and was run on a Burroughs B-5500 computer. A total of ninety one-hour simulation runs were made using six levels of main street volume and three combinations of turning movements.

Results of the field studies agreed with the conclusions of earlier researchers that the relationship between the logarithmic transform of lags and gaps and the probability of acceptance follows a cumulative normal distribution. Other events, such as service times and the time a driver hesitates before moving into the intersection upon the availability of an acceptable lag or gap, appeared to be normally distributed.

Results of the simulation runs were not surprising and were in general agreement with the findings of other researchers.

CHAPTER I

INTRODUCTION

Unprecedented traffic growth during the past decade has resulted in a greater interest in the study of traffic flow phenomena, especially the behavior of traffic at intersections. Historically, studies of the operational characteristics of traffic have, for the most part, been empirical. In more recent years, theoreticians have attempted to describe traffic flow processes by mathematical equations. While both empirical and analytical approaches have contributed to the understanding of traffic, each possesses serious limitations.

The parameters of interest, or measures of effectiveness, of traffic flow at intersections are subjects to wide variations, requiring many hours of field observations to establish meaningful "average" values. Under field conditions, the observed data is usually influenced by many environmental roadway and traffic conditions, the effects of which are difficult to evaluate and control.

As for the analytical approach, the simple analytical models which have been suggested have often been far removed from real world conditions, and those which were developed for realistic traffic conditions have tended to be exceedingly complex.

In order to fully evaluate the effectiveness of a traffic control device, it is necessary to test all the operational characteristics under a wide variety of conditions. It is also desirable to study the effects of certain parameters (e.g., volume, turning movement, etc.) one at a time while holding all others constant. Simulation by electronic computer provides a method of conducting a controlled experiment and of gathering large amounts of data.

By definition, "simulation" is an imitation. Simulation of an intersection is to imitate its operation and to study its behavior under different traffic and roadway conditions.

A computer model of an intersection consists of a series of decision making processes, mathematical equations and/or table assignment procedures. With the development of the high-speed, large-storage computers, these repetitive operations can be performed at a very low computer-real time ratio.

Background

Although a number of simulation studies have been made for signalized intersections, little attention has been given to the simulation of the two-way stop. This has probably been due to the lack of suitable mathematical models to describe driver behavior at the two-way stop.

One of the first contributions to the study of the two-way stop was made by Raff (1)*. This study of the merging problem lead Bissell (2) and Wagner (3) to research further gap acceptance distributions and express these distributions by mathematical models. Using a simplified model, Snell (4) showed that the use of a distribution for des-

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*Numbers in parentheses refer to similarly numbered references in List of References at end of thesis cribing gap acceptance is more realistic than using a single "critical" value. Kell (5) has used a composite exposite exponential function, as suggested by Gerlough (6), to calculate arrival headways.

These contributions and others have made possible the development of a computer model of an intersection controlled by two-way stop signs.

Lewis and Michael (7), and Ruiter and Shuldiner (8) developed a model for the two-way stop, but they used a single "critical" gap size. Kell (5) in his simulation study used a log-normal gap acceptance distribution as developed by Bissell (2); however, it has been found that these distributions are affected by driver-behavior characteristics which vary with location and geometrics of the intersection.

Objective

The broad objective of the proposed research was to simulate on a digital computer a street intersection controlled by two-way stop signs using available empirical data and supplementary field data and, by using the simulation model, to study the operational characteristics of the intersection.

CHAPTER II

PROCEDURE

After a thorough study of existing data available in the literature, it was found that supplementary data would be required to provide adequate inputs for the simulation model. Following the literature search and a study and evaluation of existing data, the study procedure consisted of three broad phases:

1. An empirical study which involved collection, reduction, and analysis of supplementary field data.
2. Development of computer model.
3. Conducting experimental runs of the simulation model and interpretation of results.

Empirical Study

Collection of Data

Three intersections were studied with the results from each being averaged. The data were collected during daylight hours on week days in fair, dry weather at each intersection. Observations were made for a one-hour period at each intersection during the following times of day:

1. AM - Off Peak
2. AM - Peak
3. PM - Off Peak
4. PM - Peak

This is a total of twelve hours of data studying the operational characteristics of the two-way stop.

Three intersections, all located in the Atlanta area, were selected for study:

1. Covington Highway at Wesley Chapel Road
2. North Highland Avenue at Amsterdam Avenue
3. Moore's Mill Road at Peachtree Battle Avenue.

These intersections were selected to provide examples of urban and rural usage of this type of control. Figures 1, 2, and 3 show the physical layout of each intersection. Each intersection, as noted, is a two-lane major street intersected by two-lane low-speed local streets. Caution was used in the selection to eliminate geometric peculiarities and deviations from "average" traffic flow patterns.

A preliminary study using a 40-minute roll of black and white movie film on a time-lapse movie projector was conducted to determine the best method of data collection. This study also provided a check for parameters that needed detailed study. This study indicated the need of the following data:

1. Arrival of vehicles at the intersections.
2. Hesitation time of driver after the commencement of an acceptable gap or lag (termed "starting time").
3. Service time for side street vehicles
4. Lag and gap acceptance distributions.
5. Turning movement relationship to service times and acceptance distributions.

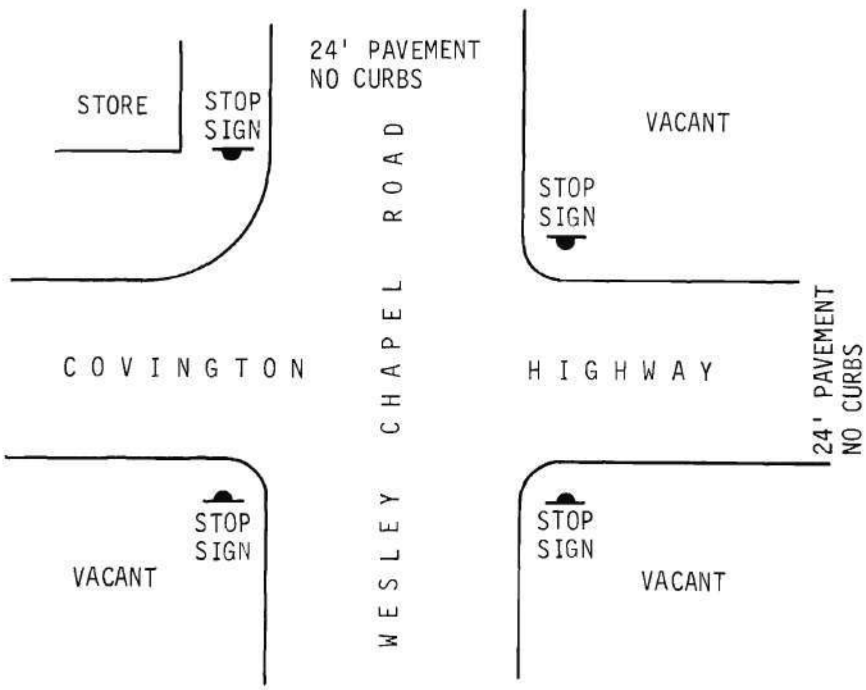
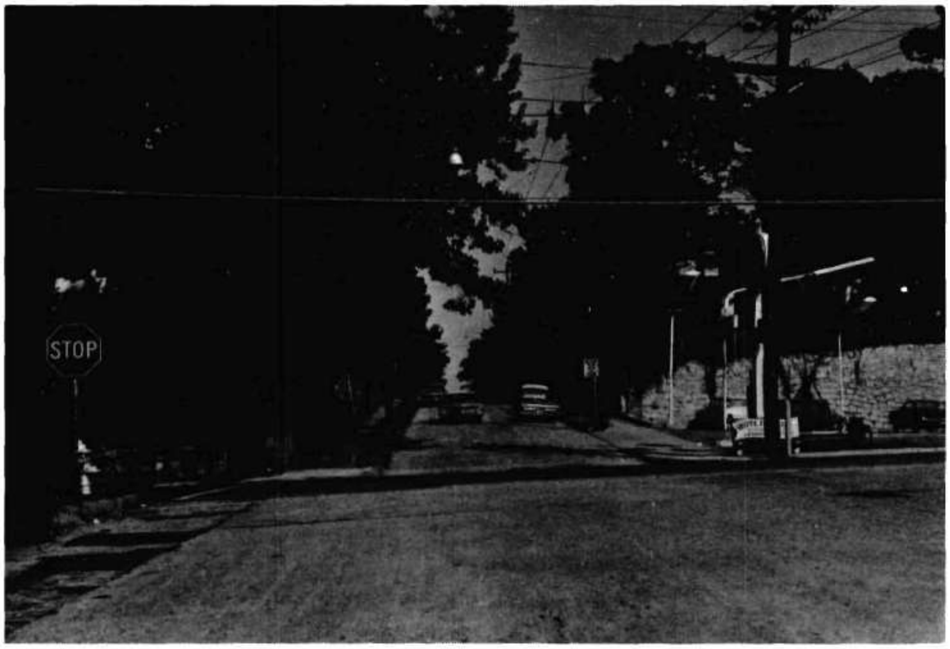


Figure 1. Intersection Diagram of Covington Highway at Wesley Chapel Road.



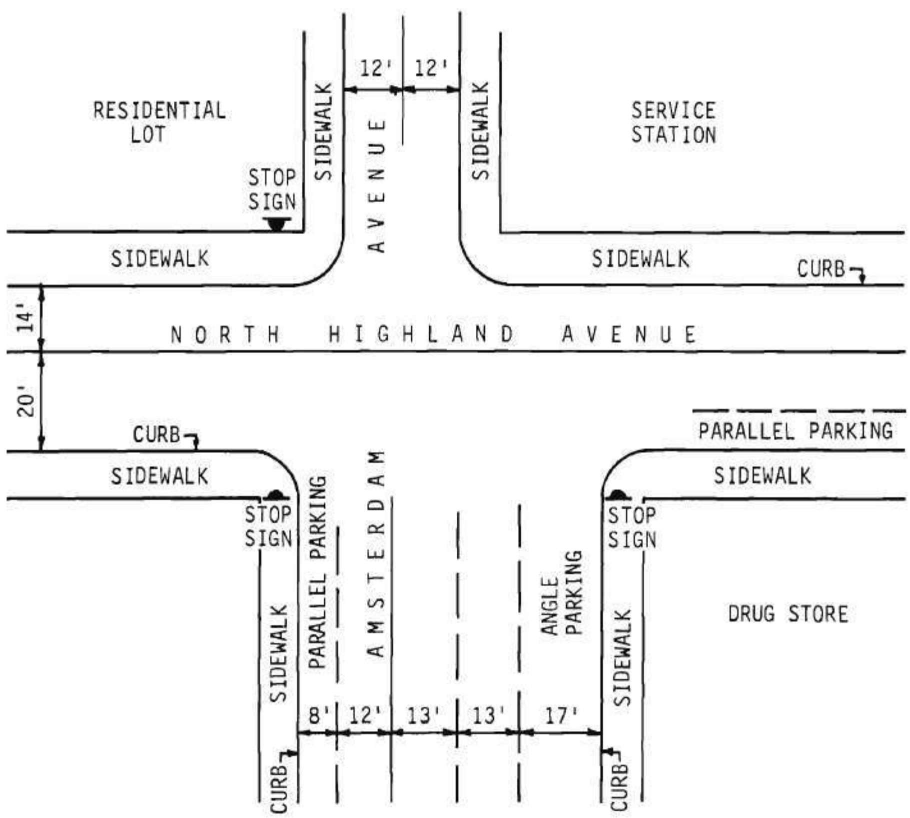


Figure 2. Intersection Diagram of North Highland Avenue at Amsterdam Avenue.

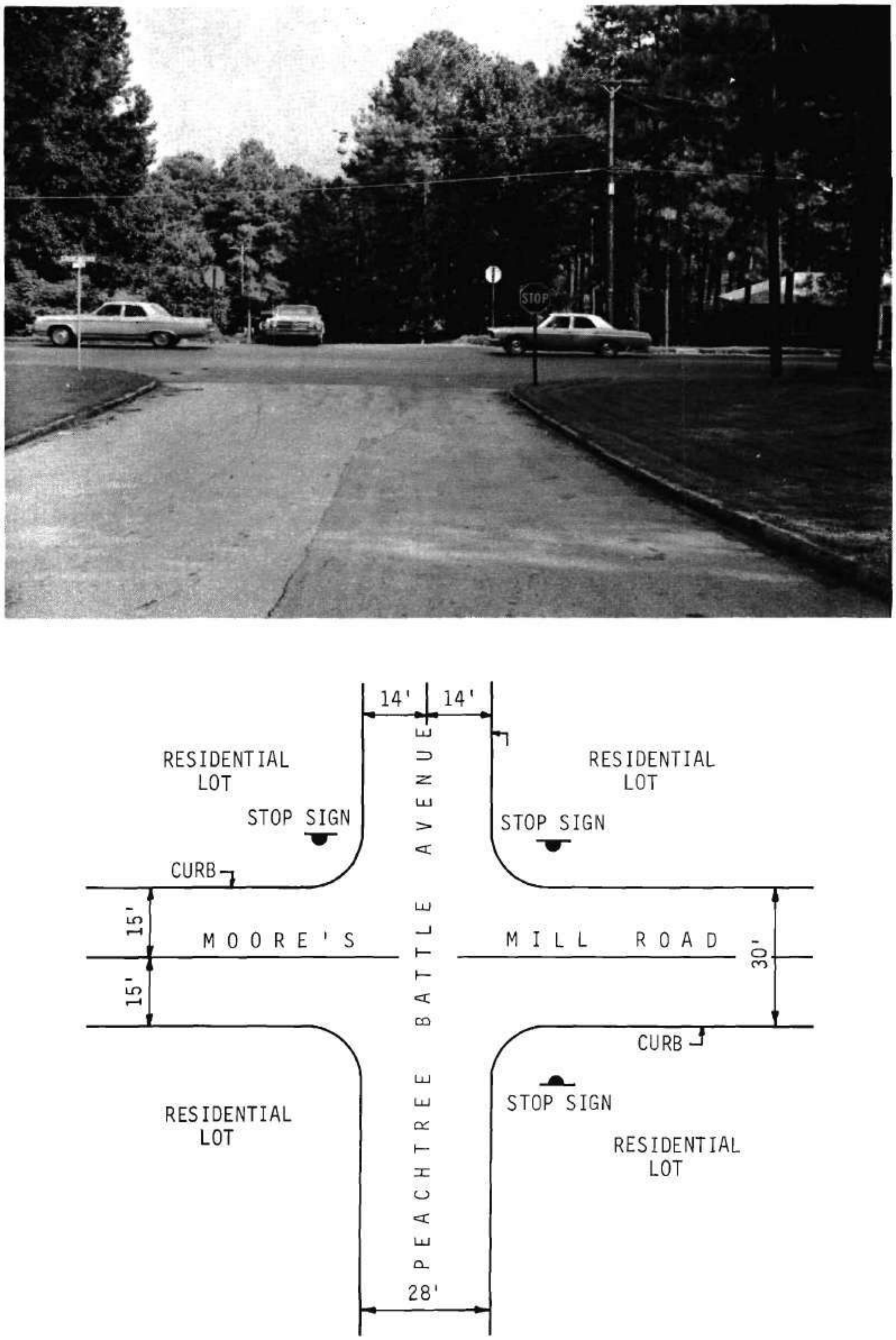


Figure 3. Intersection Diagram of Moore's Mill Road at Peachtree Battle Avenue.

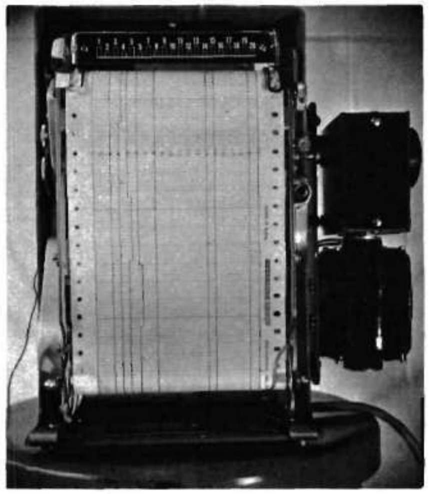
A side street vehicle was considered to have arrived at the intersection when the vehicle either stopped or reached its lowest speed. This usually occured when the vehicle's front bumper was roughly adjacent to the stop sign. A side street vehicle was considered to have departed from the intersection when its back bumper crossed an imaginary line which coincided with the farthermost pavement edges of the street approaches perpendicular to direction of movement.

In this report, the term "starting time" refers to the time the driver hesitated at the stop sign prior to his entrance into the intersection. It is equal to the difference between the time an acceptable gap or lag began and the time the service began.

By definition, service time for side street vehicles began when the vehicle commenced acceleration to enter the intersection and ended when the vehicle departed the intersection.

The data were collected by two observers operating a 10 push-button micro-switch control panel, electrically connected to an Esterline-Angus 20-pen event recorder. Figure 4 shows the equipment used. The event recorder chart was operated at 1 inch per second by means of an external motor. This allowed observations to be read from the chart directly to one tenth of a second. Figure 4 shows a sample of the data and the channel arrangement.

The equipment was operated from a private automobile parked on the side street approximately 70 feet from the near pavement edge of the main street to insure little interference with normal operation.



CHANNEL NO.	DATA RECORDED
1	NEAR MAIN STREET VEHICLES
3 & 4	NEAR SIDE STREET VEHICLES
5 & 6	FAR SIDE STREET VEHICLES
8	FAR MAIN STREET VEHICLES
14	NEAR SIDE STREET RIGHT TURNS
15	NEAR SIDE STREET LEFT TURNS
19	FAR SIDE STREET LEFT TURNS
20	FAR SIDE STREET RIGHT TURNS

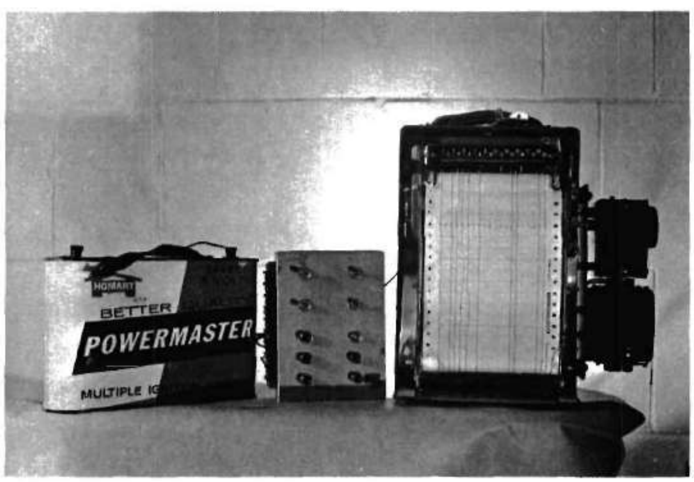


Figure 4. Sample of Data on Chart Paper and Equipment.

The reference line for the passage of main street vehicles was established as an imaginary line which coincided with the farthermost pavement edges of the side street approaches. An arrival of a main street vehicle was recorded when the vehicle's back bumper crossed this line. Main street arrivals were defined in this manner to allow main street vehicles to clear the intersection; thus, an available gap could be accepted immediately without physical conflict.

A total of 3040 acceptance and rejection decisions were made, 604 relating to lags and 2436 relating to gaps, during the twelve hours of data collections.

Reduction of Data

As in any empirical study, the reduction of field data was a time-consuming process. To aid in the reduction process the data were recorded on I. B. M. format sheets and punched on cards that could be processed by a sorter. The information removed from the charts included:

1. Delay of the queue leader.
2. Service time for each turning movement.
3. Starting time for each vehicle.
4. Lags and gaps rejected by each vehicle.
5. Lags and gaps accepted by each vehicle.
6. Presence of opposite side street vehicles.

All of the important reduced data can be found in the Appendix.

Analysis of Data

The analysis of data involved the determination of mathematical models for a computer input. Probability distributions for the following data were studied:

1. Lag and gap acceptance
2. Service time
3. Starting time.

Lag and gap acceptance was handled in a similar manner to Wagner's approach (3). The lags and gaps were stratified according to turning movement and grouped into one-second intervals using integer values as the upper limit. No lag or gap larger than 13 seconds was rejected so that the range was from one to 13 seconds.

For each class interval the frequency of acceptances, A_i and rejections, R_i, and the interval sample size, $N_i = A_i + R_i$, were determined. The probability (or proportion) of acceptance for each interval, P_i, was estimated by the statistic:

$$P_i = \frac{A_i}{N_i}$$

Due to the small sample sizes for some turning movements at Covington Highway and Moore's Mill Road, there was no distinction made between intersections for lag and gap acceptance. The frequency at each interval for each movement was summed for the three intersections and the probability computed by the above statistic.

The service time data were stratified according to turning movement and intersection for analysis. However, the probability distributions used in the simulation model were based on a combination of data for the three intersections. A percent cumulative distribution was computed for one second intervals ranging from one to five seconds using integer values as the upper limit.

Starting time data were stratified according to intersection and later summed. The analysis was the same as that for service time.

The results of this study agreed with earlier findings of Bissell (2) and Wagner (3) and gave further evidence that the relationship between the logarithm of gap and lag and the probability of acceptance follows a cumulative normal distribution curve.

A comparison of the lag and gap distributions for the left and straight movements indicated little difference between these distributions. On this basis, a combined distribution was used in the simulation model. (See Figure 5.) Figures 6-9 show the plots of the distributions on log-normal graph paper, and Figure 10 shows a comparison of others' findings with those of the author. The results are very similar.

Service time and starting time were found to fit a normal distribution. Figures 11-13 show the plot of service time for each turning movement and Figure 14 shows the comparison of the distributions for the three movements.

Starting time for each intersection is shown in Figure 15-17 and Figure 18 shows the composite of all three. This plot was used as the computer input model.

Development of Computer Model

Elements of the Simulation Model

The important criteria for an effective traffic simulation model is that every decision performed by the driver be presented accurately on the computer. This requires an understanding of the driver's decision process. After an analysis of driver's behavior at an intersection, the following list of events was incorporated

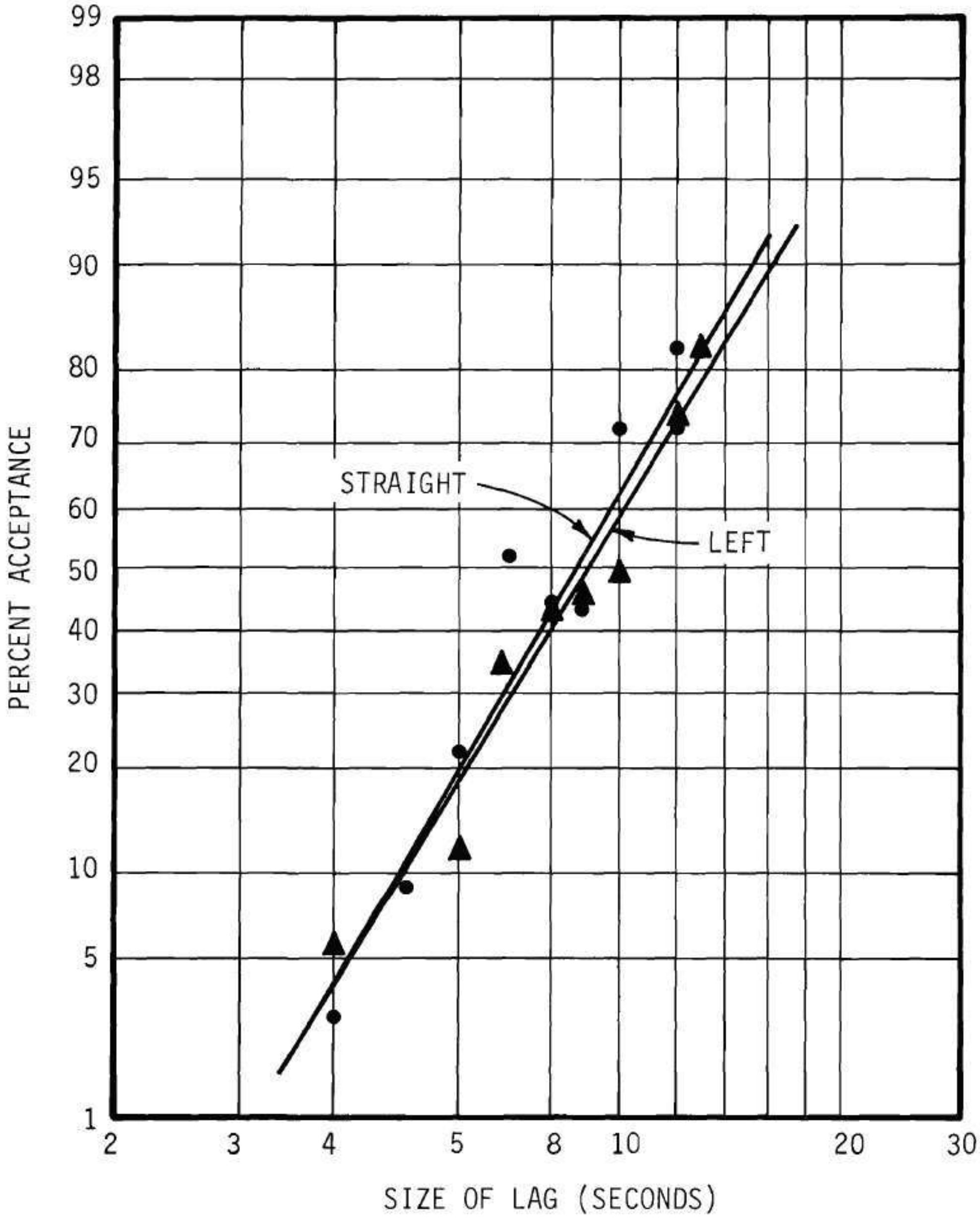


Figure 5a. A comparison of Lag Acceptance Distributions for Left and Straight Movements.

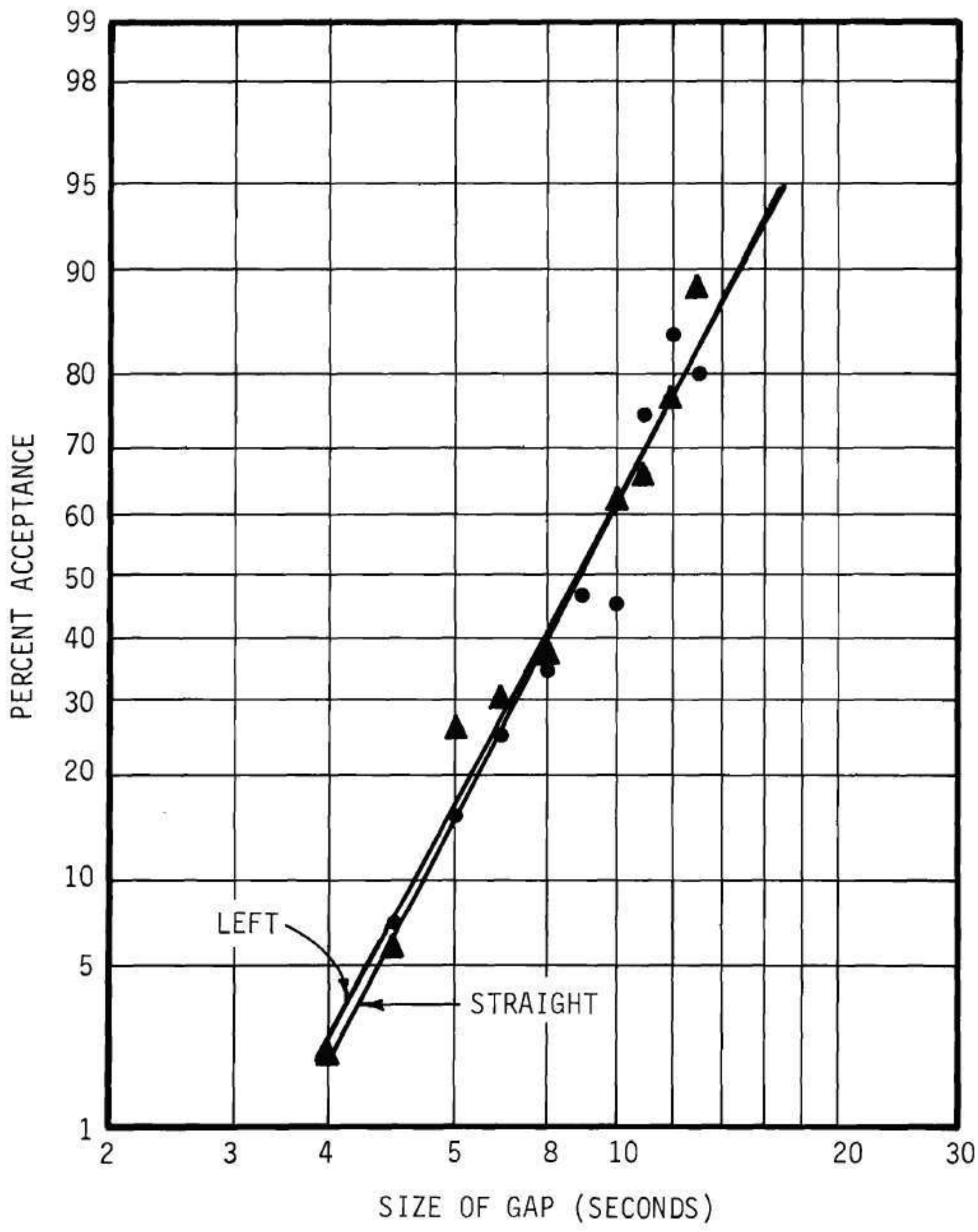


Figure 5b. A Comparison of Gap Distributions for Left and Straight Movements.

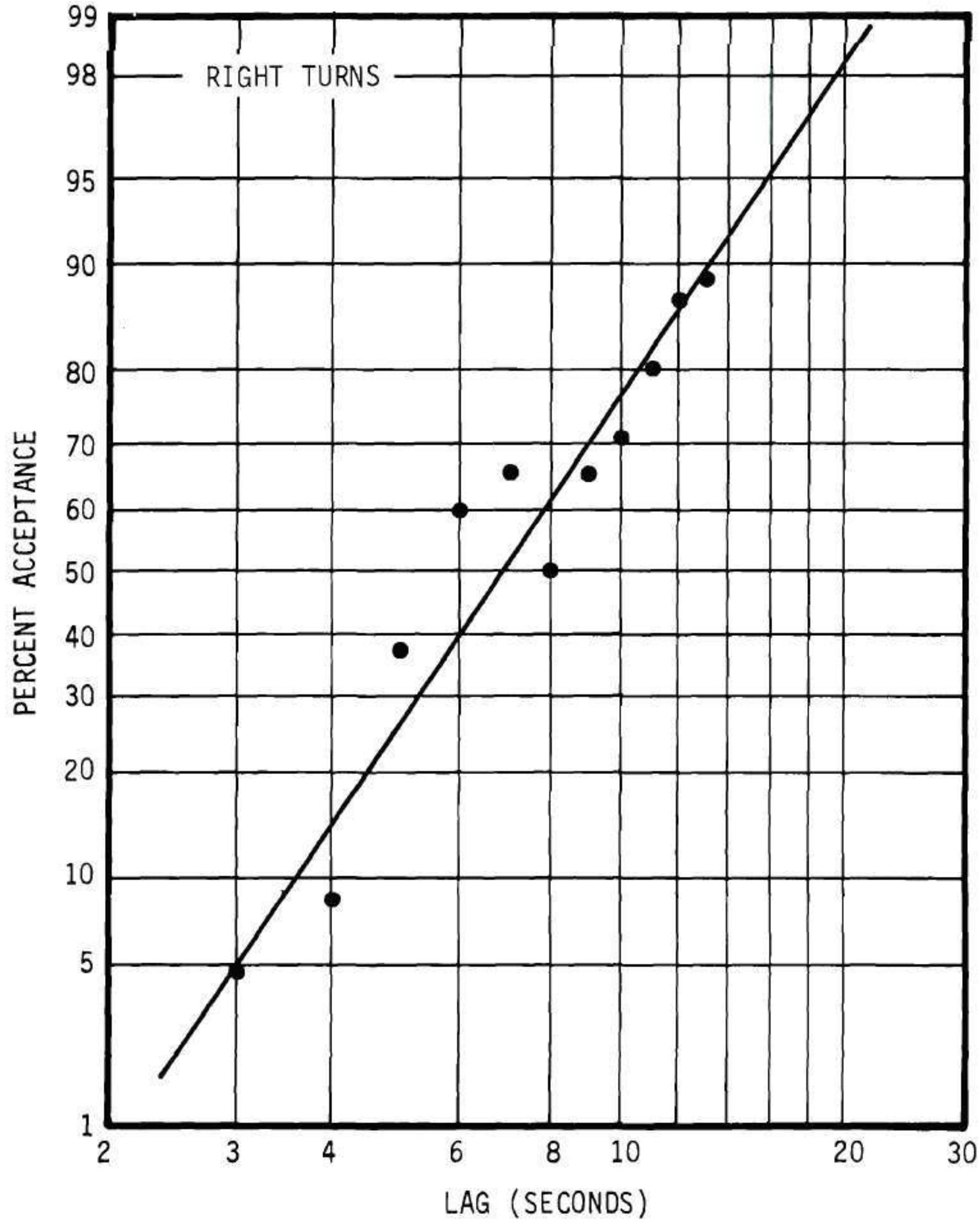


Figure 6. Percent Acceptance of Lags for Vehicles Turning Right - All Intersections Combined.

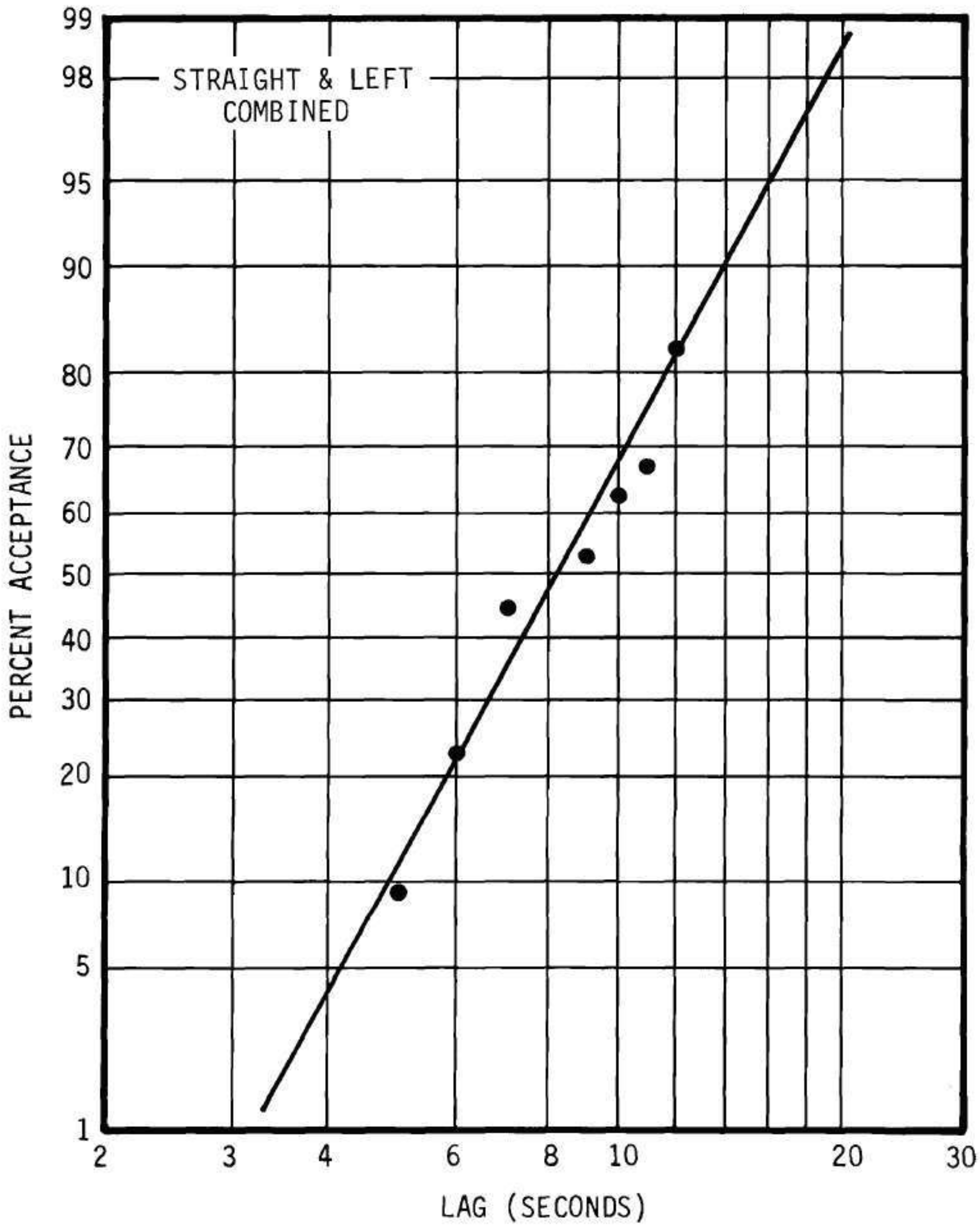


Figure 7. Percent Acceptance of Lags for Vehicles Going Straight or Left - All Intersections Combined.

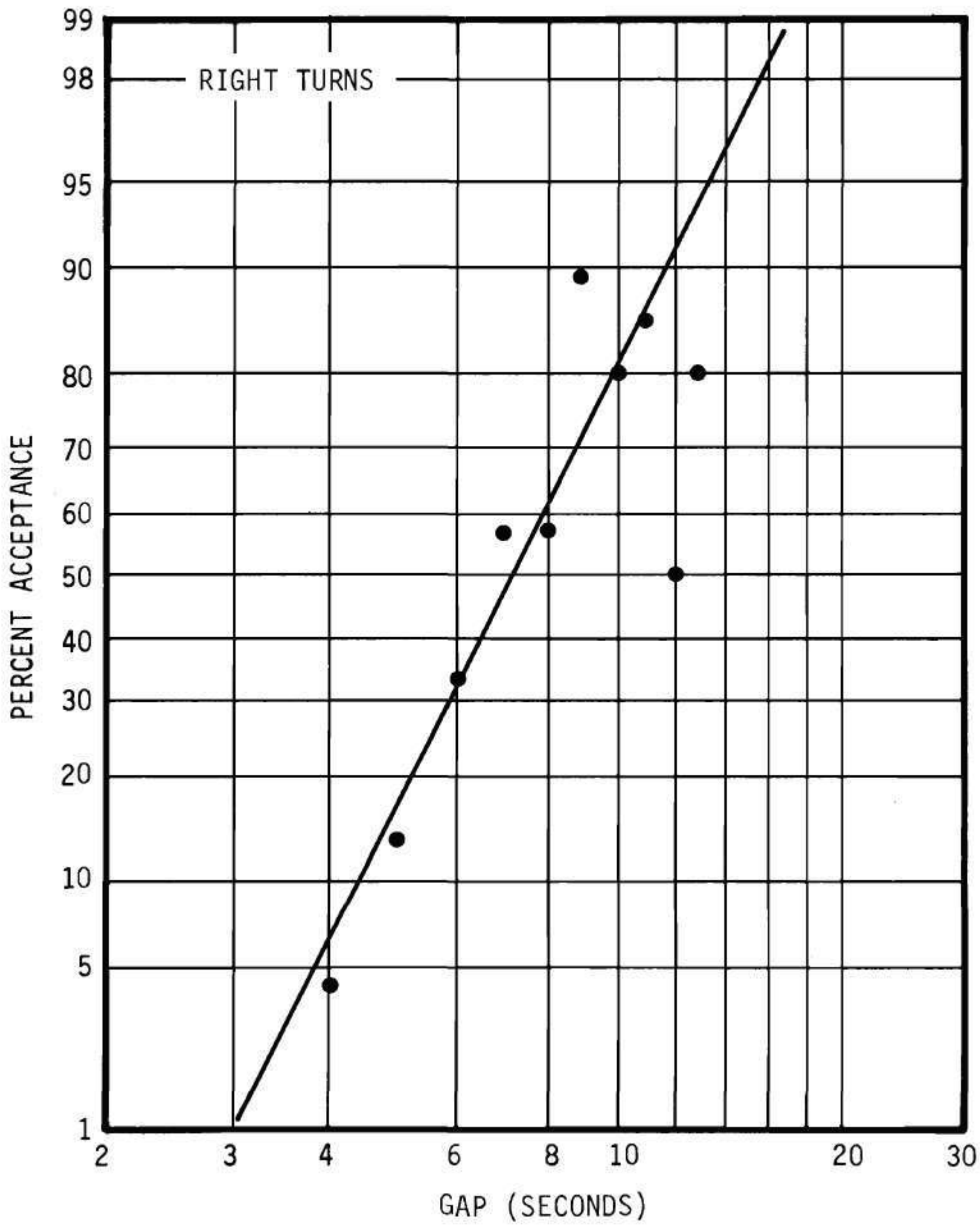


Figure 8. Percent Acceptance of Gaps for Vehicles Turning Right - All Intersections Combined.

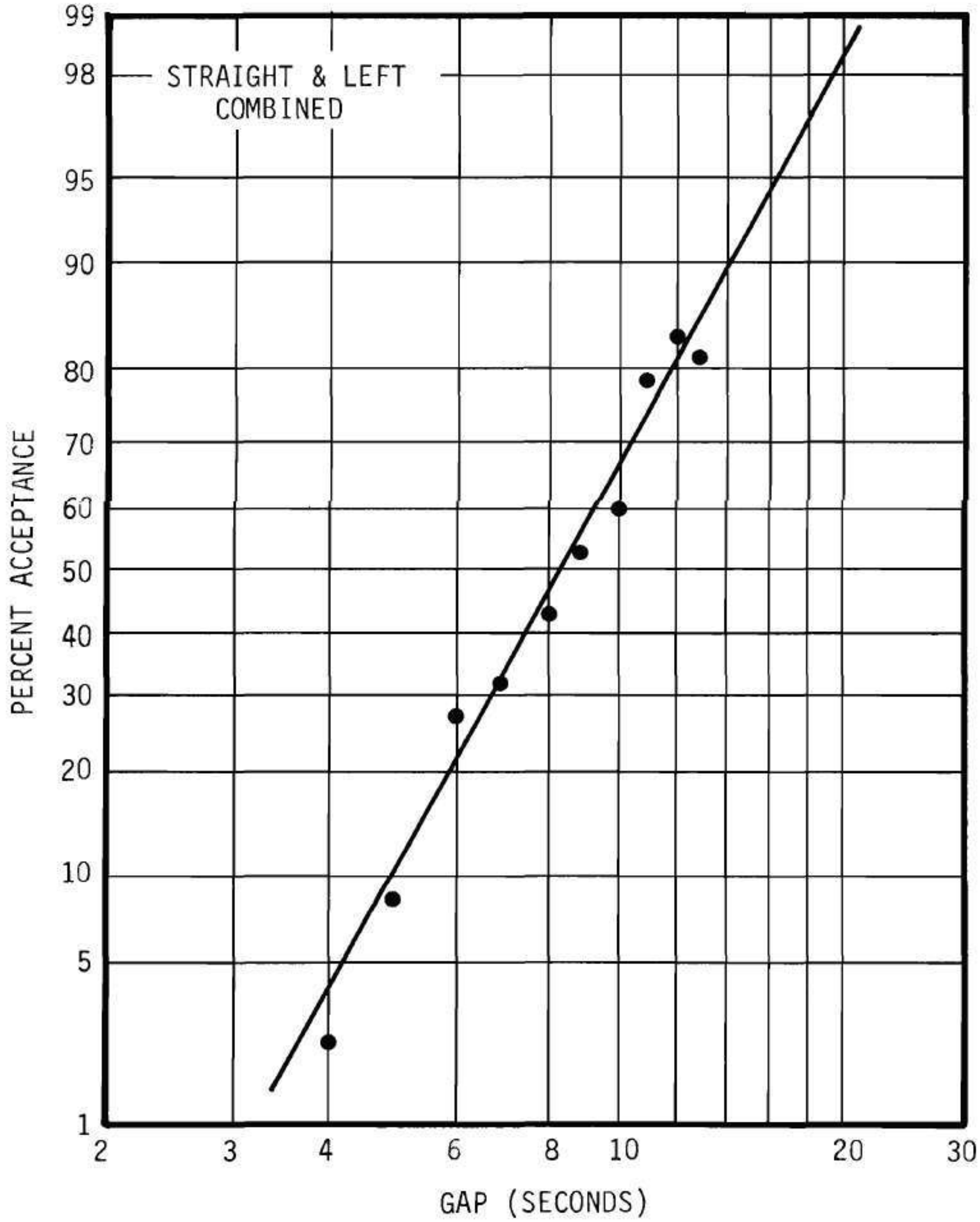


Figure 9. Percent Acceptance of Gaps for Vehicles Going Straight or Left.

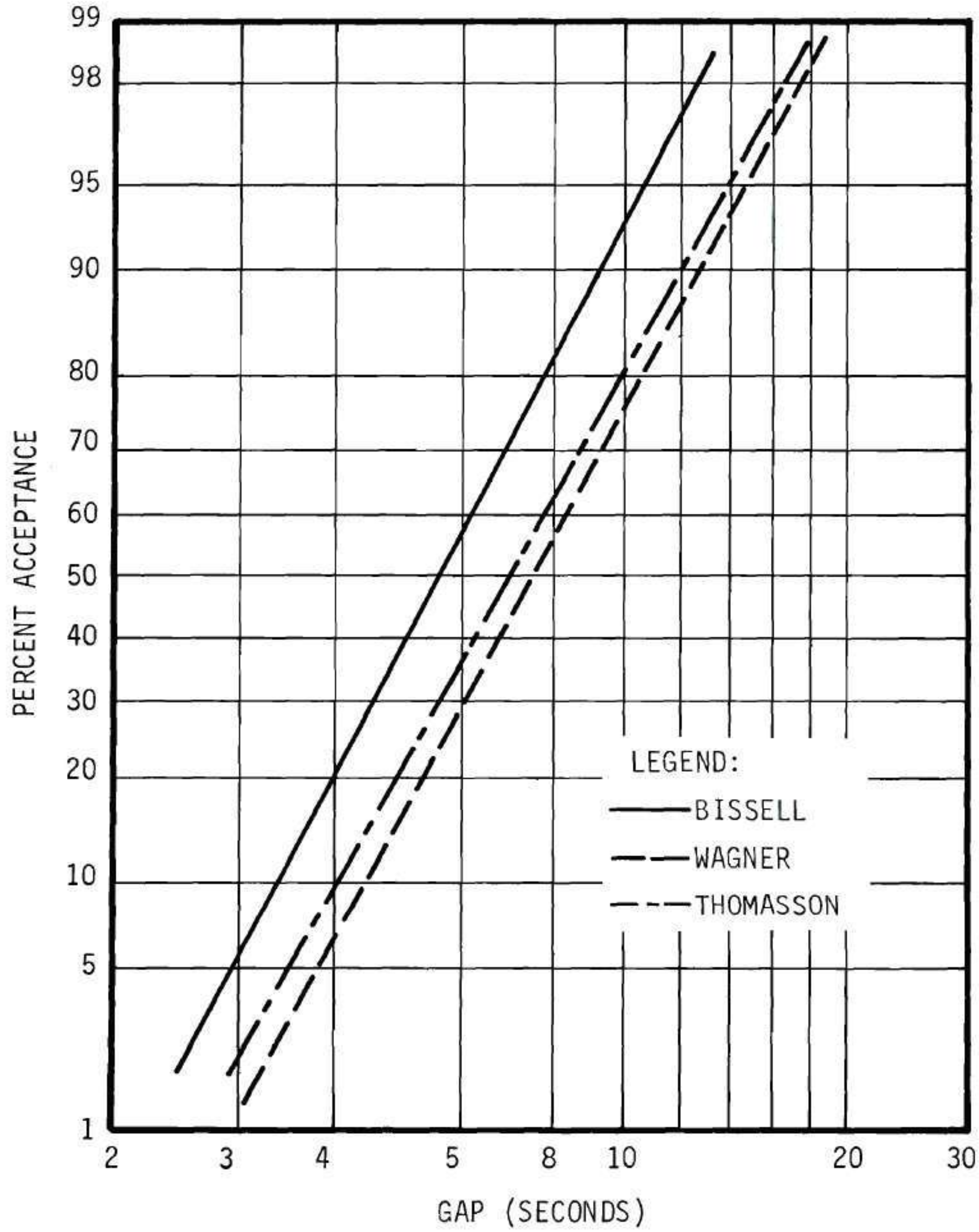


Figure 10. A Comparison of Lag and Gap Acceptance Distributions of Various Researchers.

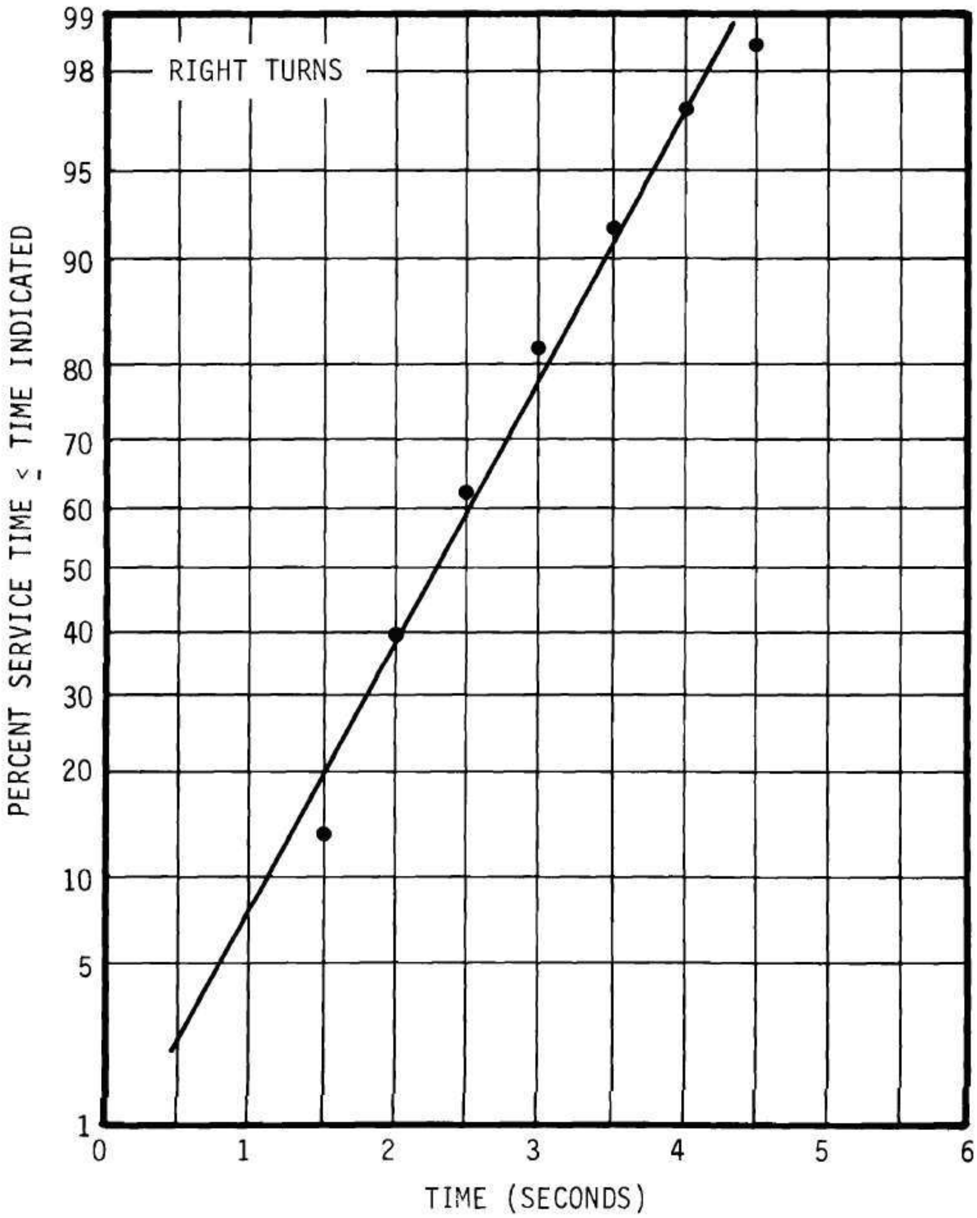


Figure 11. Service Time Distribution for Vehicles Turning Right - All Intersections Combined.

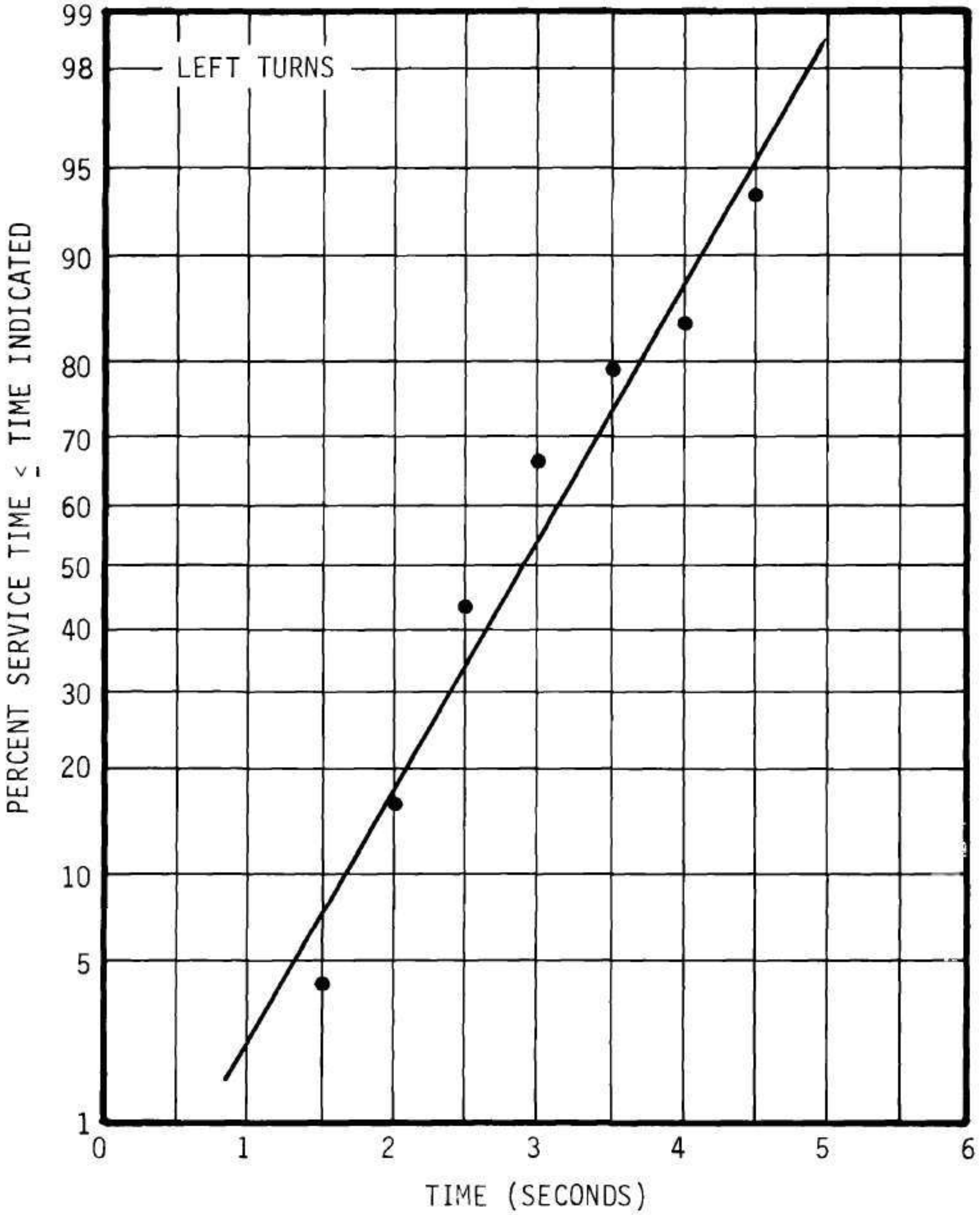


Figure 12. Service Time Distribution for Vehicles Turning Left - All Intersections Combined.

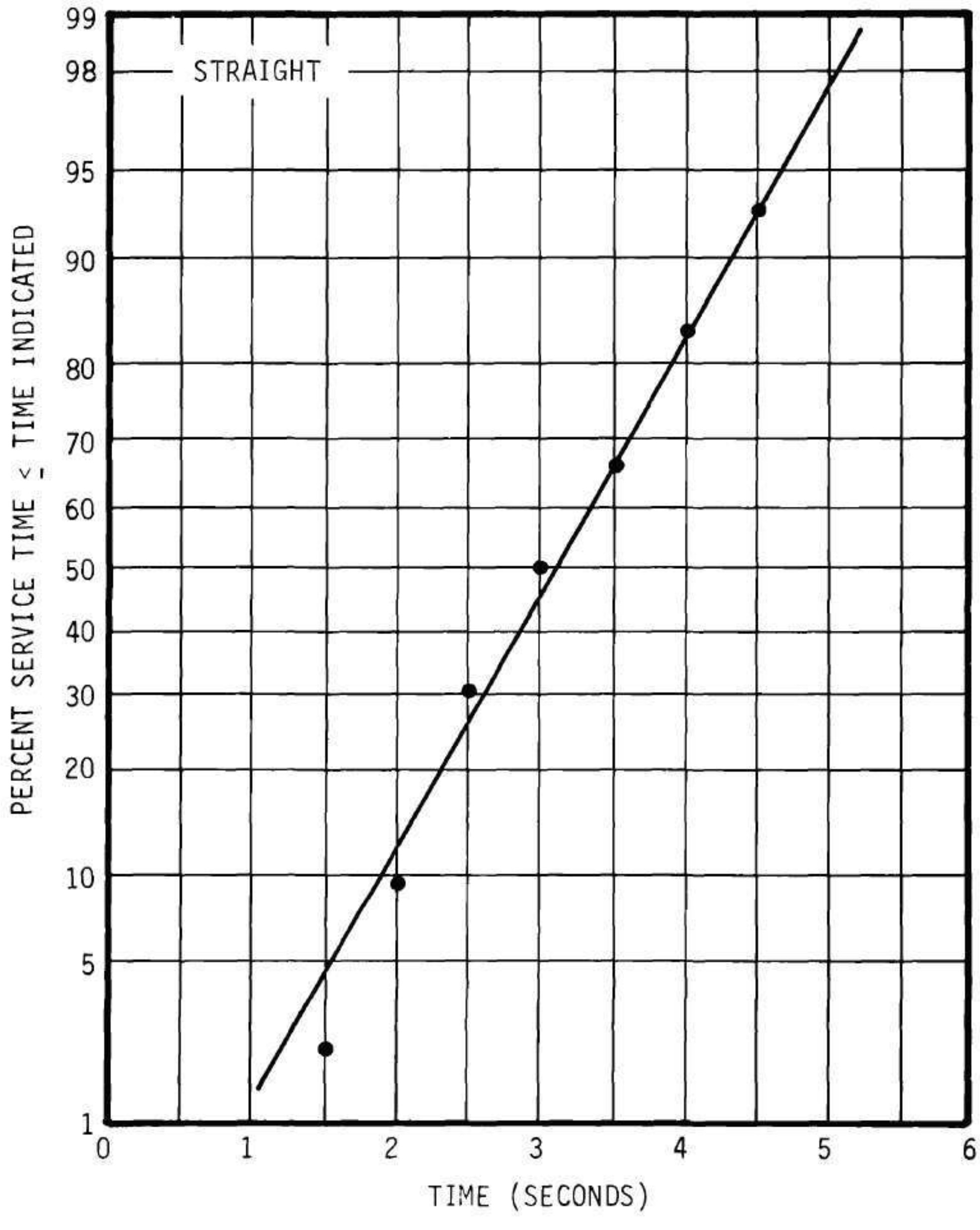


Figure 13. Service Time Distribution for Vehicles Going Straight - All Intersections Combined.

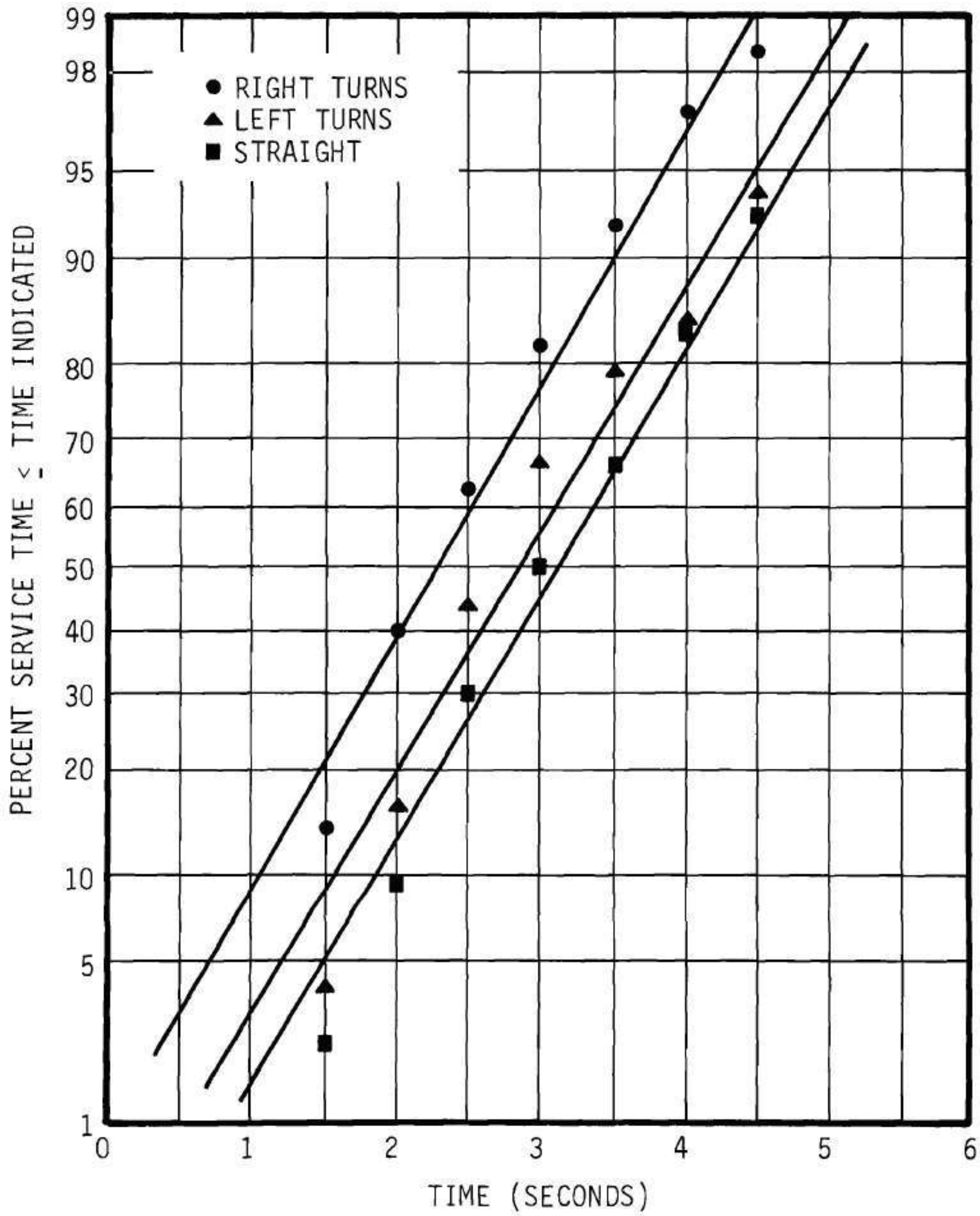


Figure 14. Comparison by Movement of Service Time Distribution for All Intersections Combined.

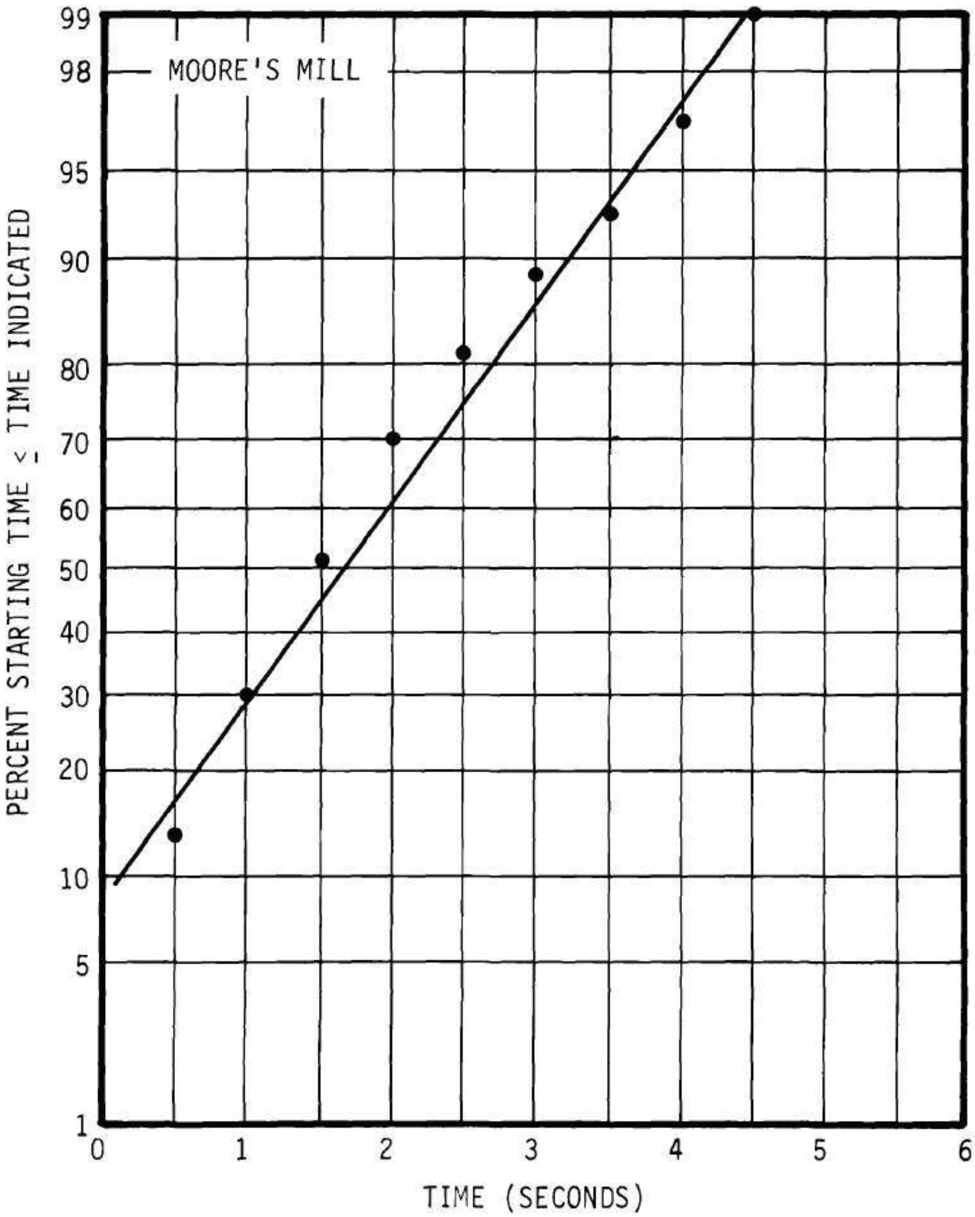


Figure 15. Starting Time Distribution for Moore's Mill Road.

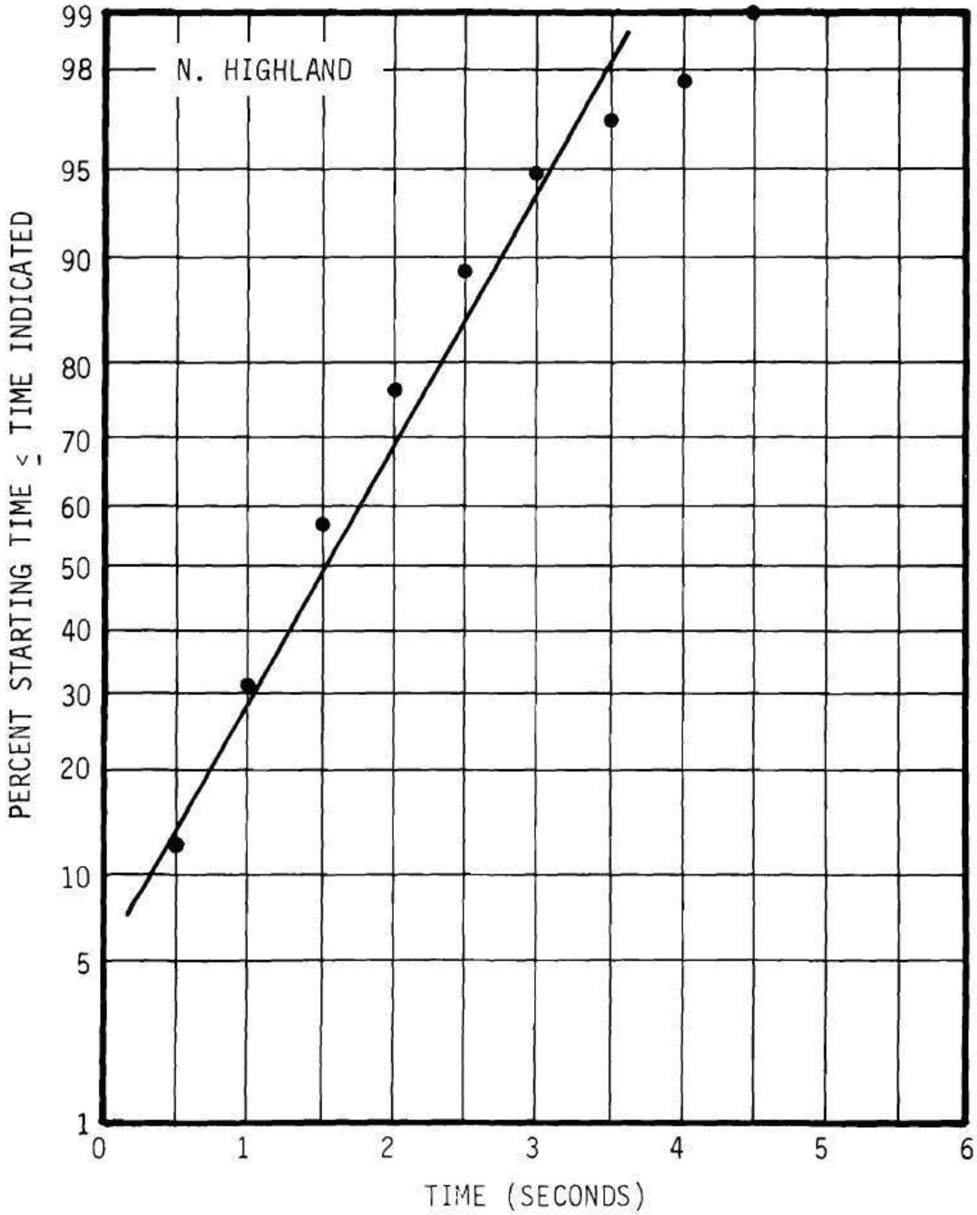


Figure 16. Starting Time Distribution for North Highland Avenue.

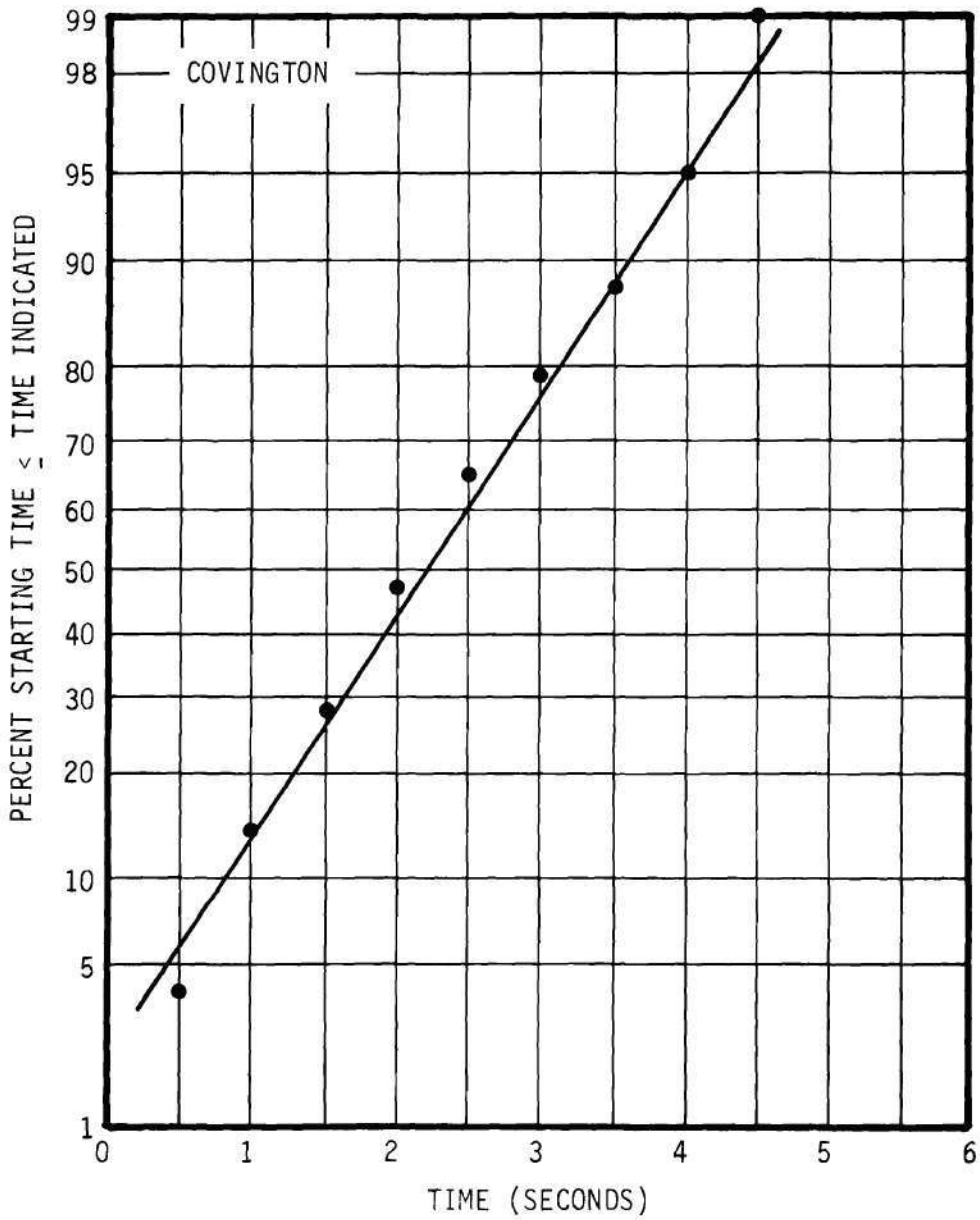


Figure 17. Starting Time Distribution for Covington Highway.

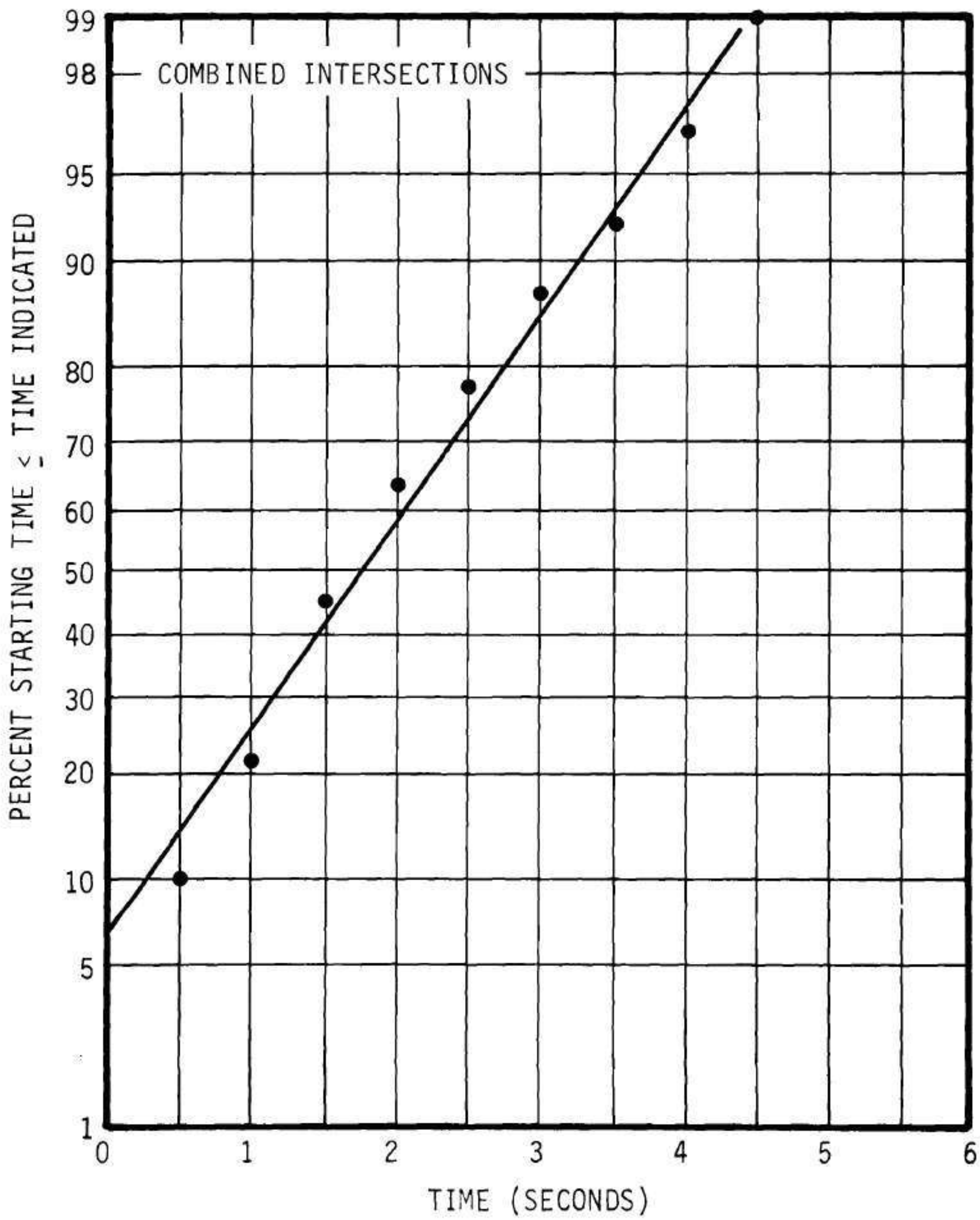


Figure 18. Starting Time Distribution for All Intersections.

into the computer program:

1. Arrival of side street vehicle.
2. Turning movement decision.
3. Check of near approach for acceptable lag or gap.
4. Check of far approach for acceptable lag or gap.
5. Recheck of near approach lag or gap.
6. Hesitation to prepare for movement. (Start Time)
7. Movement to merge. (Service Time).

The program was divided into three main blocks or processes. The first block involved all the input models as prepared from empirical data. The second block was the decision making processes using the previously mentioned list of events. The last block was the output process, printing the desired information on the operational characteristics of the two-way stop intersection.

The second block was written and validated with predetermined input and checked by manual calculations compared with the computer output.

Mathematical Input Models

The turning movement decision was based on a preselected percentage and a random assignment of movements to each new side street vehicle.

The lag and gap acceptance model was based on a Monte Carlo process using a log-normal distribution. This procedure was complicated by the nature of the distribution; however, by generating a random number from 0 to 1, an associated or corresponding normalized value, T, from a normal distribution with mean zero and standard deviation of one was selected by a table assignment procedure. The value of "T" ranging from -2.50 to +2.50 was converted to the logarithm of lag or gap by the equations whown on Figures 19-22. The lags and gaps were then computed from their logarithms using the following equations:

$$\text{Lag (sec)} = 10^{L}$$

$$\text{Gap (sec)} = 10^{G}$$

where "L" and "G" refer to the logarithm of lag and gap, respectively.

The service time and starting time models were handled in a similar manner. A random number from 0 to 1 was used to determine the corresponding "T" value from a normal distribution of mean zero and standard deviation of one. The parameters were computed using the following equations:

$$\text{Service Time} = \left| T \times \text{Standard Deviation} \pm \text{Mean} \right|$$

$$\text{Starting time} = \left| T \times \text{Standard Deviation} \pm \text{Mean} \right|$$

Gaps were determined by the time spacing between main street vehicles arrivals. Lags were determined by the time spacing between the arrival of the second vehicle constituting a main street gap and the arrival of a side street vehicle.

The vehicle arrival model was based upon one similar to that used by Kell (5) in his simulation study. Spot checks of empirical data indicated that this model was sufficient. On the side street approach, arrivals were assumed to occur at the end of the queue if one existed. A small study of arrivals at a stop sign indicated that little difference existed between arrivals some point away from the intersection and at the end of the queue.

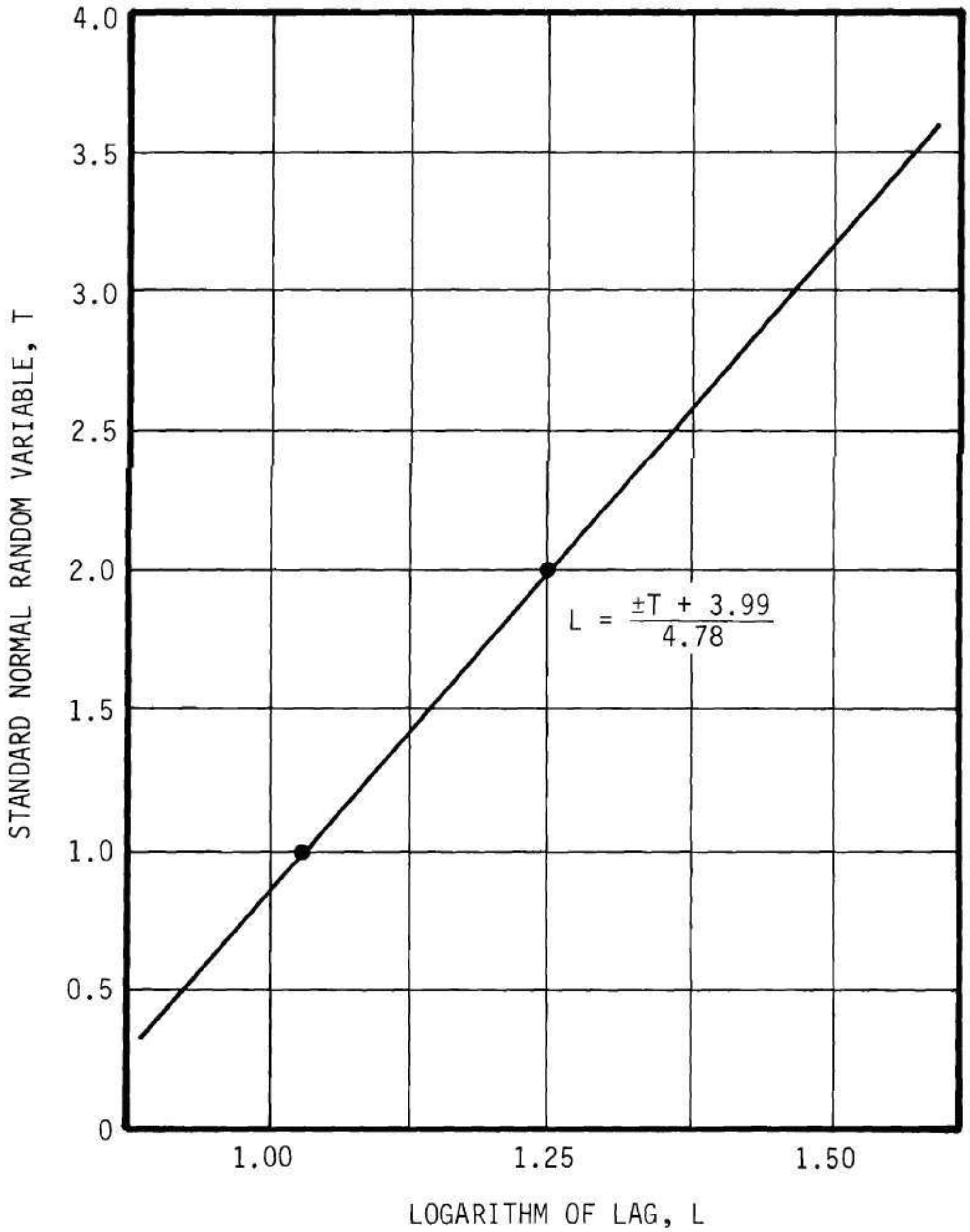


Figure 19. Standardized Normal Random Variable Related to Logarithm of Lags -- Vehicles Turning Right.

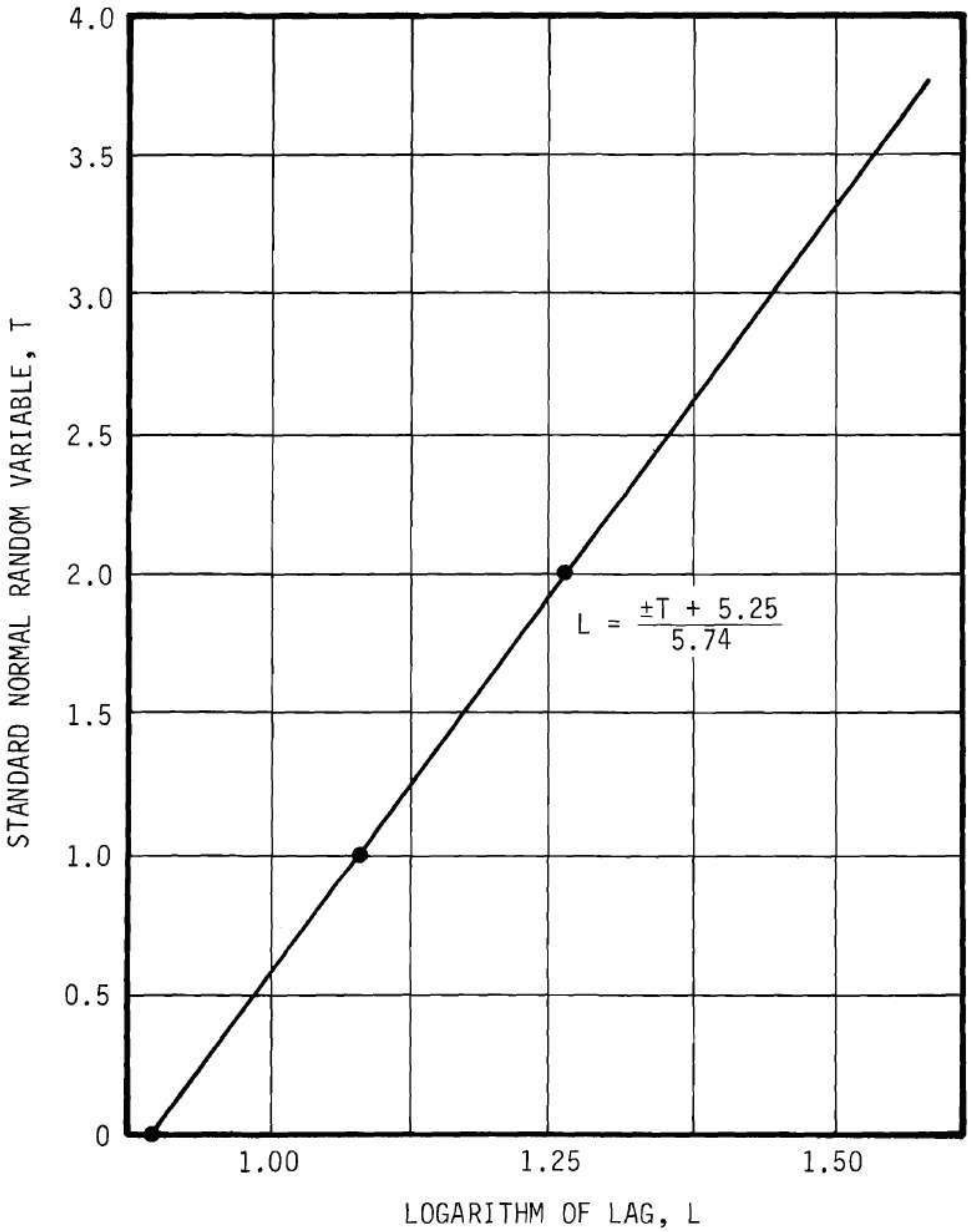


Figure 20. Standardized Normal Random Variable Related to Logarithm of Lags -- Vehicles Going Left and Straight.

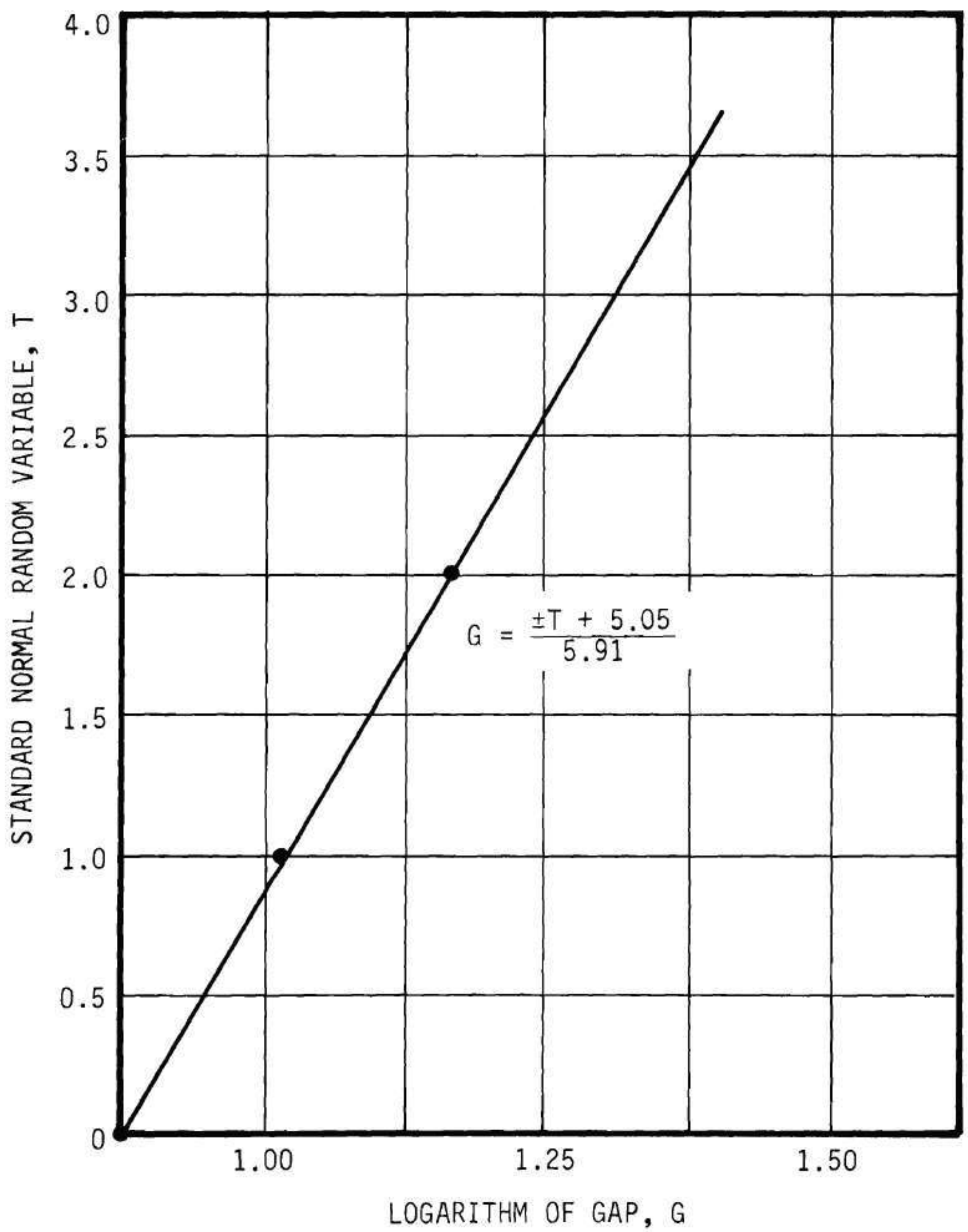


Figure 21. Standardized Normal Random Variable Related to Logarithm of Gaps -- Vehicles Going Right.

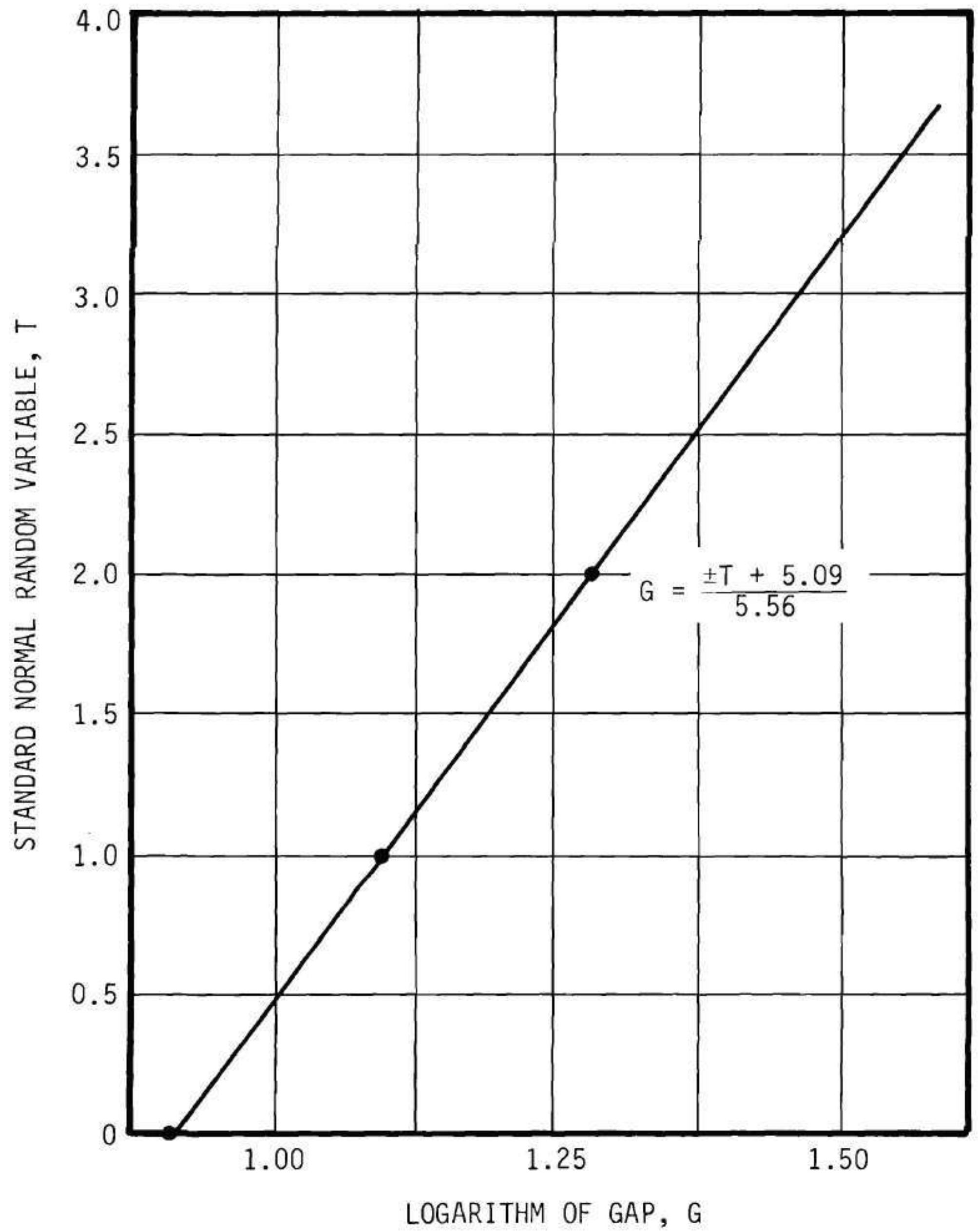


Figure 22. Standardized Normal Random Variable Related to Logarithm of Gaps -- Vehicles Going Left and Straight.

Verbal Description of Model Process

Verbally, one can describe the operation of the simulation model as follows: main street and side street vehicles are gererated at some preselected volume rate. The arrival of the first side street vehicle is considered first. A turning movement is assigned and some acceptable lag and gap size is calculated according to the turning movement. Two cases were considered: right turning and crossing movements.

If the vehicle is turning right, only the near approach main street vehicles are considered. The lag is calculated and compared with the generated lag assigned. If the acceptable lag is larger, then a service time and a starting time are calculated based upon the turning movement. Then the vehicle is cleared from the intersection (i. e., the system is updated), and the next side street vehicle is considered. If this next vehicle is in the same approach as the first and its arrival was before the first vehicle was "served", a delay in the queue is determined by the difference between the elapsed time of the first vehicle and the arrival time of the second vehicle. The second vehicle is now treated as the lead car, and the delay in the queue is recorded. If the second vehicle to arrive is in the opposite side street approach, the vehicle is treated as a lead vehicle with no queue delay. However, there is a delay as queue leader which is the summation of rejected lag and gap(s), starting time, and service time. If a lag in the main street is smaller than the generated lag, the side street vehicle rejects it. This lag is recorded as part of the total delay. A generated gap is assigned and compared to gaps in the main street until one is acceptable. The sum of rejected lag and gap (s) constitutes the queue leader delay. When an acceptable gap is available, a service time and a starting time are assigned and this vehicle is "cleared"; the delay is recorded. A new side street vehicle is then considered next.

If the vehicle is crossing the intersection, he must consider both approaches. The near approach is checked first until an acceptable spacing occurs, then the far approach is inspected. When the far approach is clear for merging, the driver rechecks the near approach gap, and acts accordingly. He is served as described previously.

The process continues for a simulated time of one hour at which time a new volume rate is selected.

Figure 23 shows a simple flow chart of the programs indicating the basic steps in the decision process. A detailed flow chart is included in the Appendix.

The program was written in ALGOL EXTENDED 60 and a Burroughs B-5500 computer was used. The estimated real time to computer processor time ratio was 82:1.

Simulation Runs

The main objective of the project is to describe the operational characteristics of the two-way stop. One of the best measures of effectiveness is the parameter of average delay per side street vehicle. This delay is the sum of all delays divided by the hourly side street volume. Included in total delay is:

1. delay in queue
2. delay of queue leader while waiting for acceptable

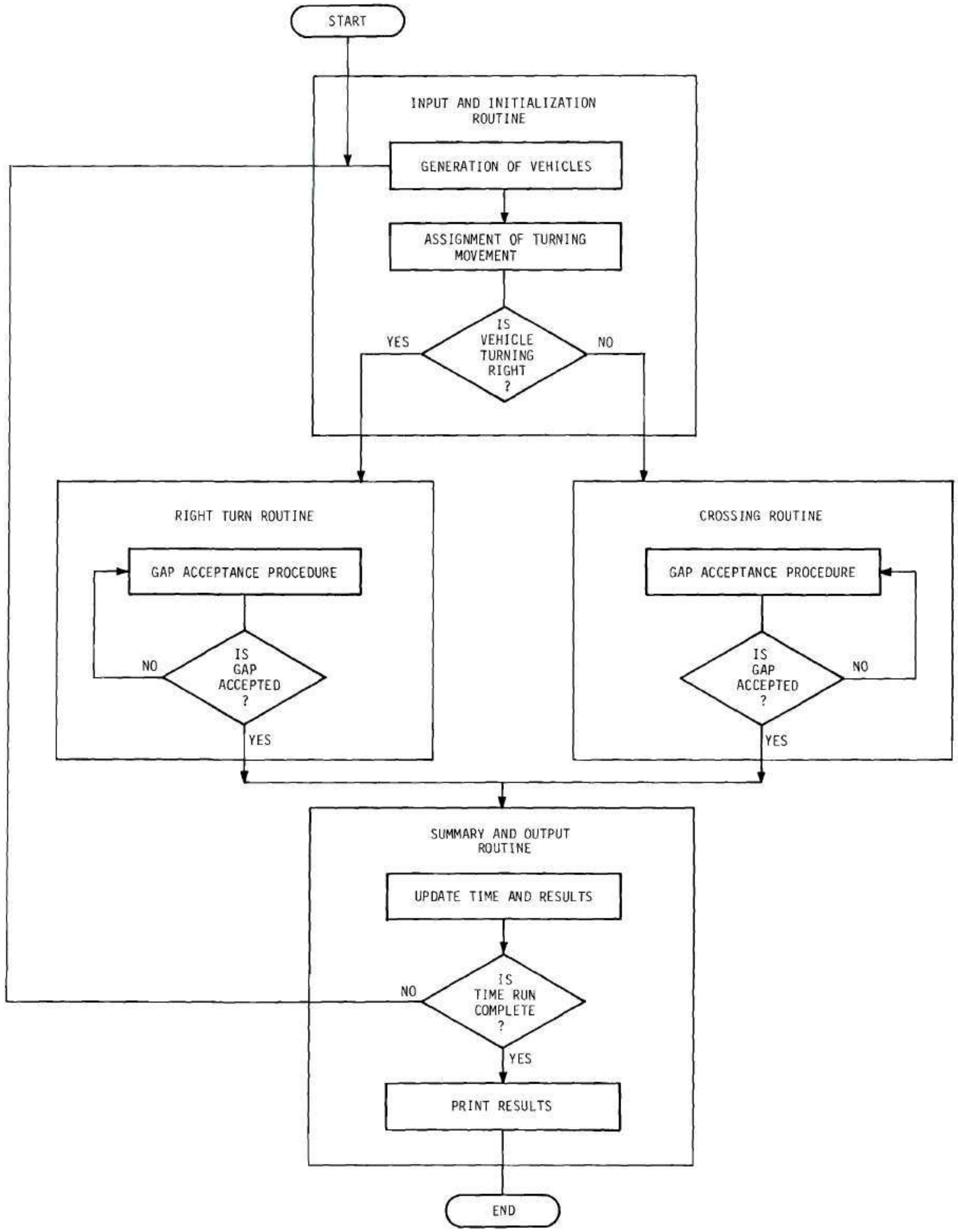


Figure 23. General Flow Chart of Computer Program.

gap or lag

3. hesitation or starting time

4. service time.

Starting time and service time are least affected by side street or main street volumes. Service time is a function of the geometrics of the intersection and the driver-vehicle relationship. Starting time involves a reaction time of the driver. These parameters, may however, be slightly influenced by the concept introduced by Wagner (3) called "pressure of demand." The variation should only be a small percentage of the total delay.

Since delay in the queue and delay of the queue leader are functions of side street and main street volumes, it is desirable to conduct simulation runs to determine the effect of each. The main street volume (total of both approaches) was varied from 200 to 1200 vehicles per hour in increments of 200 vehicles per hour. The upper limit of 1200 vehicles per hour was selected, because at higher volumes, the main street approaches unstable flow. The side street volumes (total of both approaches) ranged from 50 to 250 vehicles per hour in increments of 50 vehicles per hour. At volumes greater than 250 vehicles per hour, use of a traffic signal may be warranted (9). Due to the limited time of the research project the effect of directional distribution of main street traffic was not studied; however, Kell (10) has indicated that this is not an important factor. It was assumed that there was a 50-50 directional distribution of main street traffic.

The left and crossing movements (which were handled in an identical manner) were studied by setting the percentage of the right turns equal to 10, 20, and 30 per cent.

There were 90 simulation runs of one hour each. The output provided the arrival time, elapsed time, and delay for each side street vehicle printing 15 minute and 1 hour totals for each run. The delay was also divided into right and crossing movements.

The computer to real time ratio increased as the main street volume increased. This was due to the increasing complexity of operation of the model at higher volumes.

CHAPTER III

RESULTS

Average delay per side street vehicle gives a meaningful measure of the operational efficiency of the two way stop. It was the principle measure of effectiveness used in the simulation study.

As expected, average delay to the side street vehicles increased as the main street volumes increased. Not surprisingly, these increases were most pronounced at high side street volumes due to queue formation. See Figures 24-26. These curves appear to be logarithmic in form. Plots of the data on semi-log graph paper as shown in Figures 27-29 show that the data can be fitted by straight lines.

Detailed side street data are shown for 10, 20, and 30 per cent right turns respectively in Tables 15-17 in the Appendix. A study of the data indicates that increasing the percentage of the more complex left and straight movements results in increased average delay. This effect is barely noticeable, however, at low main street volumes.

The magnitude of the effect of turning movement percentages is shown by Table 1, which gives average delay of side street vehicles for a main street volume of 1200 vehicles per hour. The simulation results showed that, at the highest volumes studied, average delay to side street vehicles increased approximately 30 per cent as the percentage of crossing movements were changed from 70 to 90 per cent. This relationship is also shown by Figure 30, in which are shown lines of equal delay (30 seconds) for side street traffic having 10,

Table 1

Average delay of side street vehicles showing effect of directional distribution -- main street volume of 1200 vehicles per hour.

Per cent Right Turns	Side Street Volume, UPH 50	100	150	200	250
10	28.1	36.0	47.9	59.1	78.0
20	23.1	32.2	42.0	51.8	65.6
30	21.4	28.1	37.2	47.4	58.3

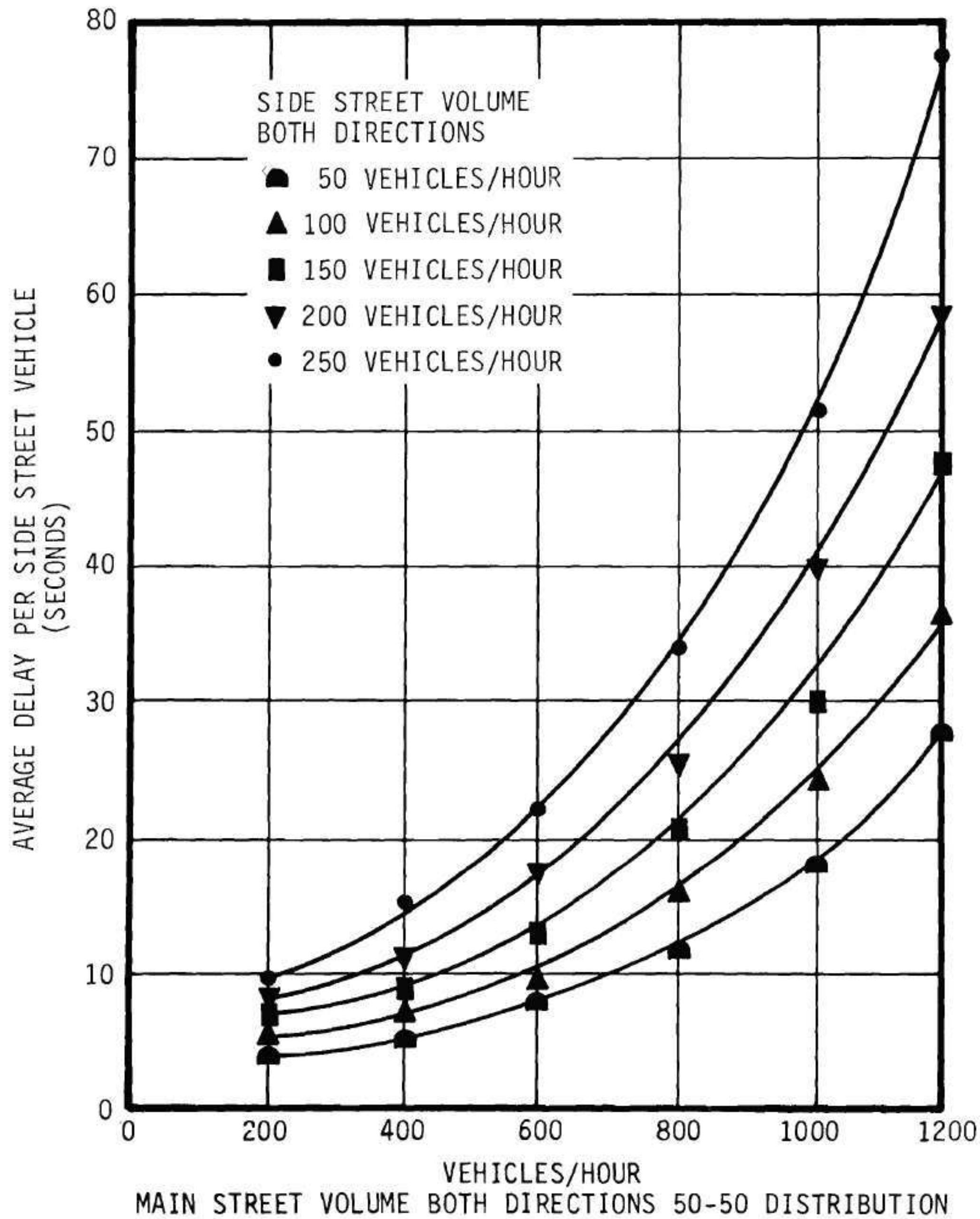


Figure 24. The Effect of Main Street Volume on Average Delay per Side Street Vehicle at Ten Percent Right Turns.

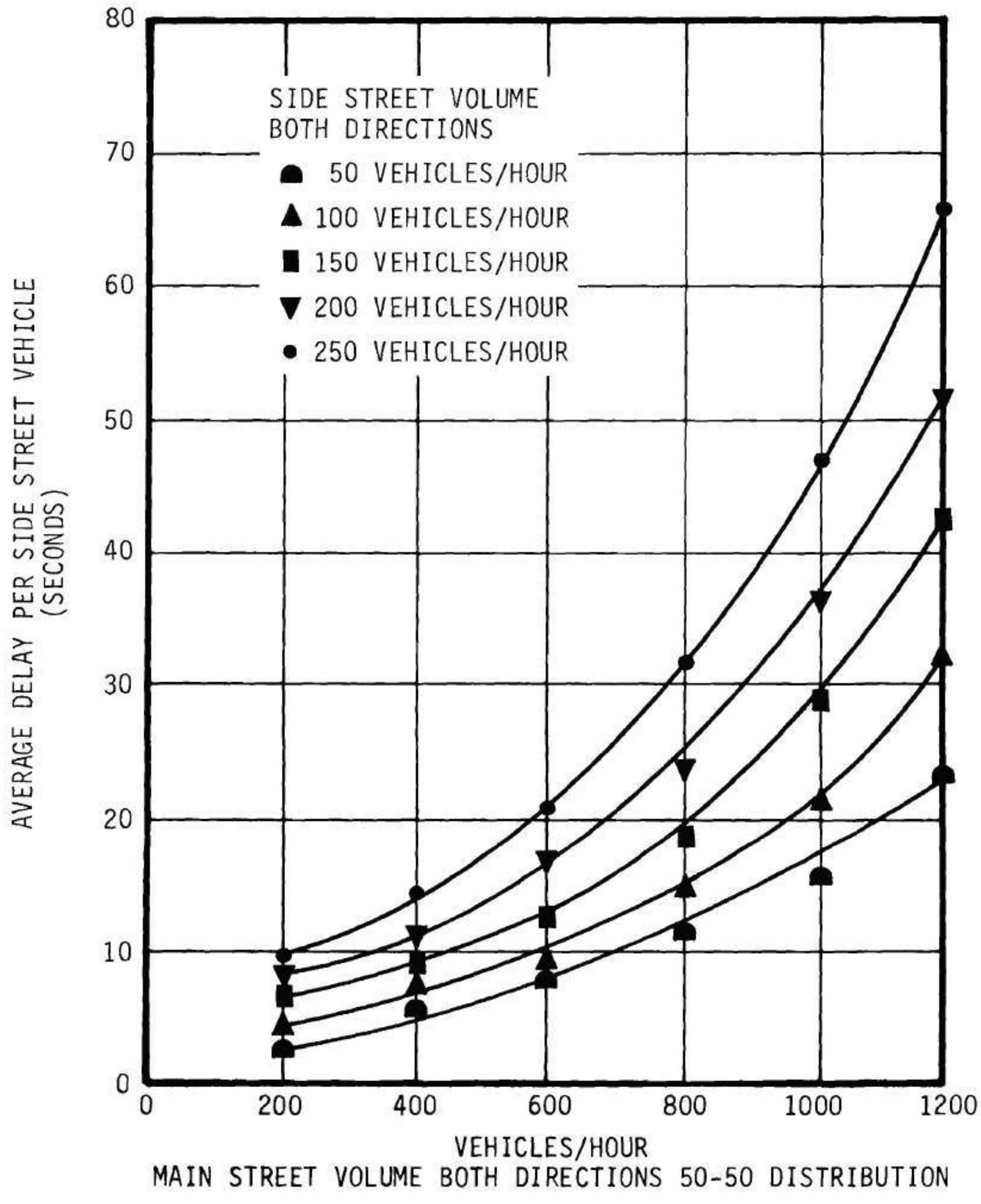


Figure 25. The Effect of Main Street Volume on Average Delay Per Side Street Vehicle at Twenty Percent Right Turns.

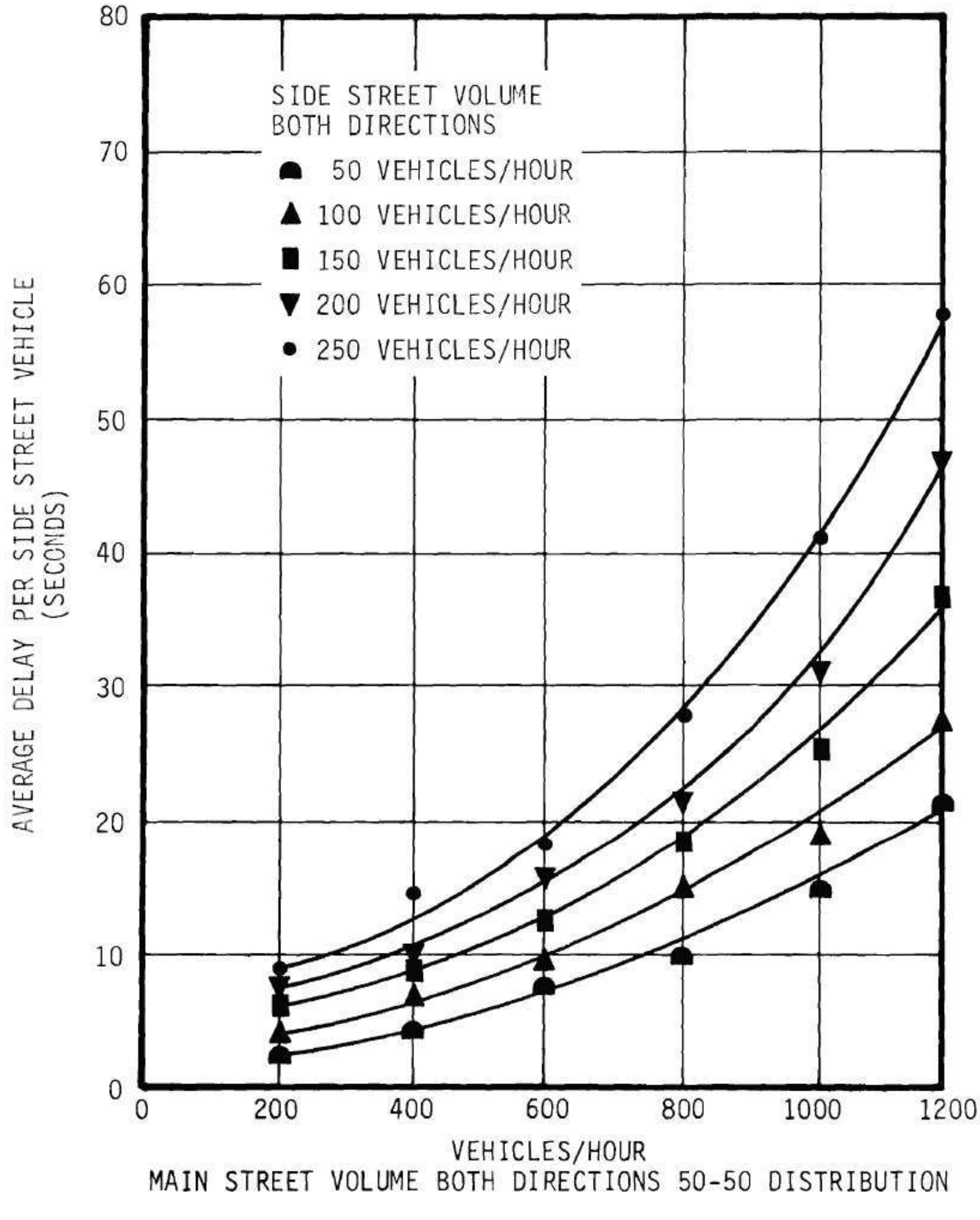


Figure 26. The Effect of Main Street Volume on Average Delay Per Side Street Vehicle at Thirty Percent Right.

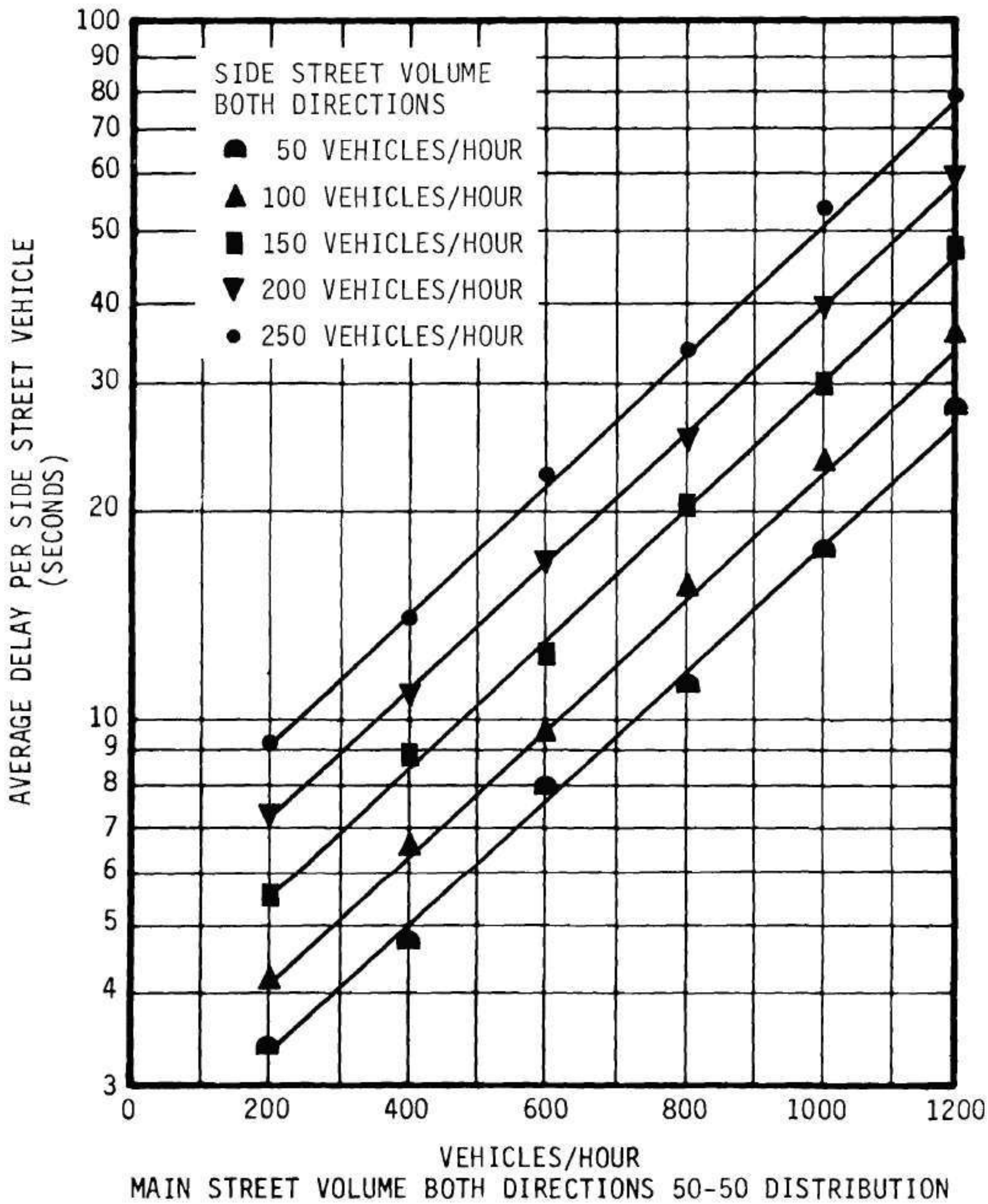


Figure 27. The Effect of Main Street Volume on Average Delay Per Side Street Vehicle at Ten Percent Right Turns.

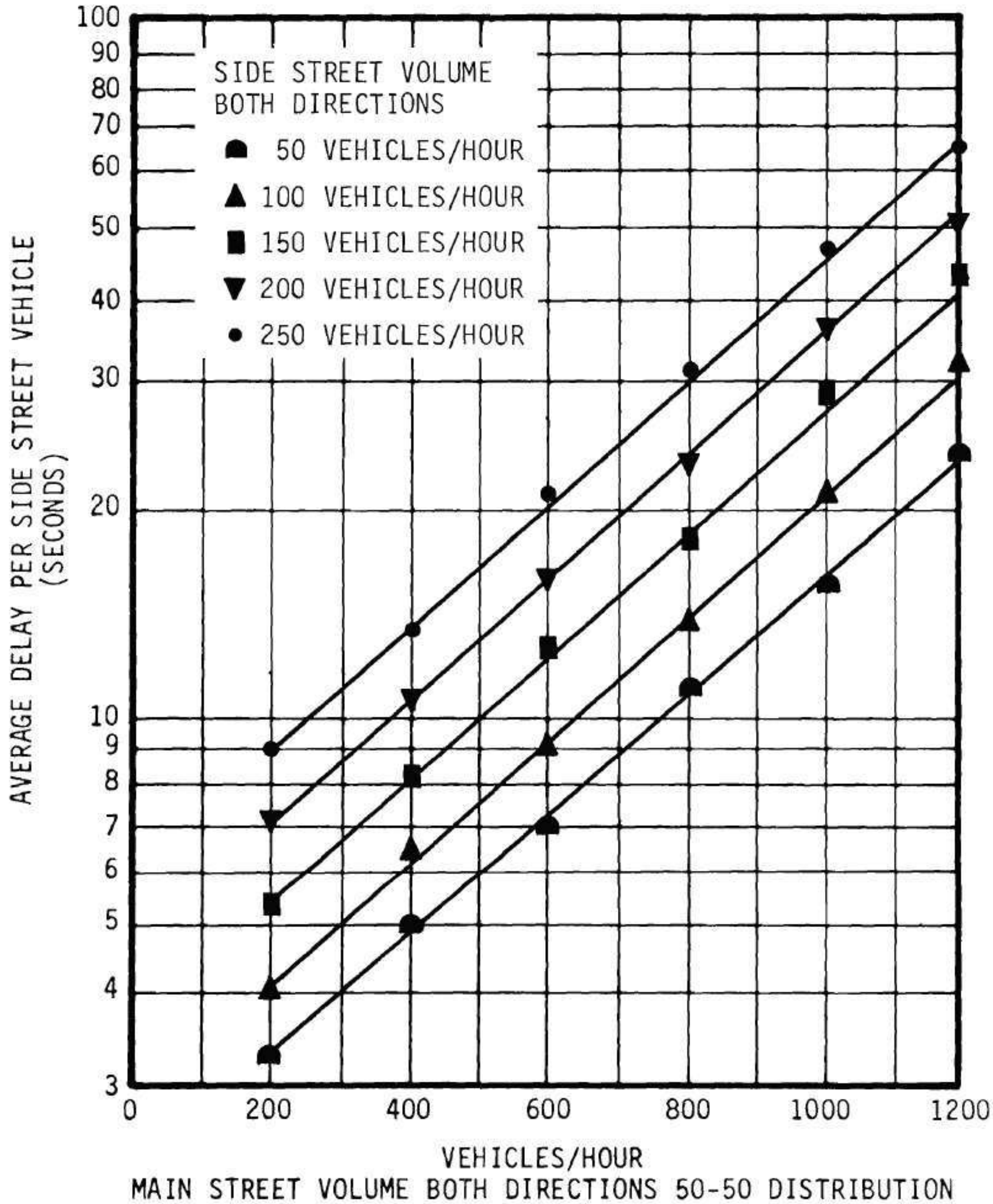


Figure 28. The Effect of Main Street Volume on Average Delay Per Side Street Vehicle at Twenty Percent Right Turns.

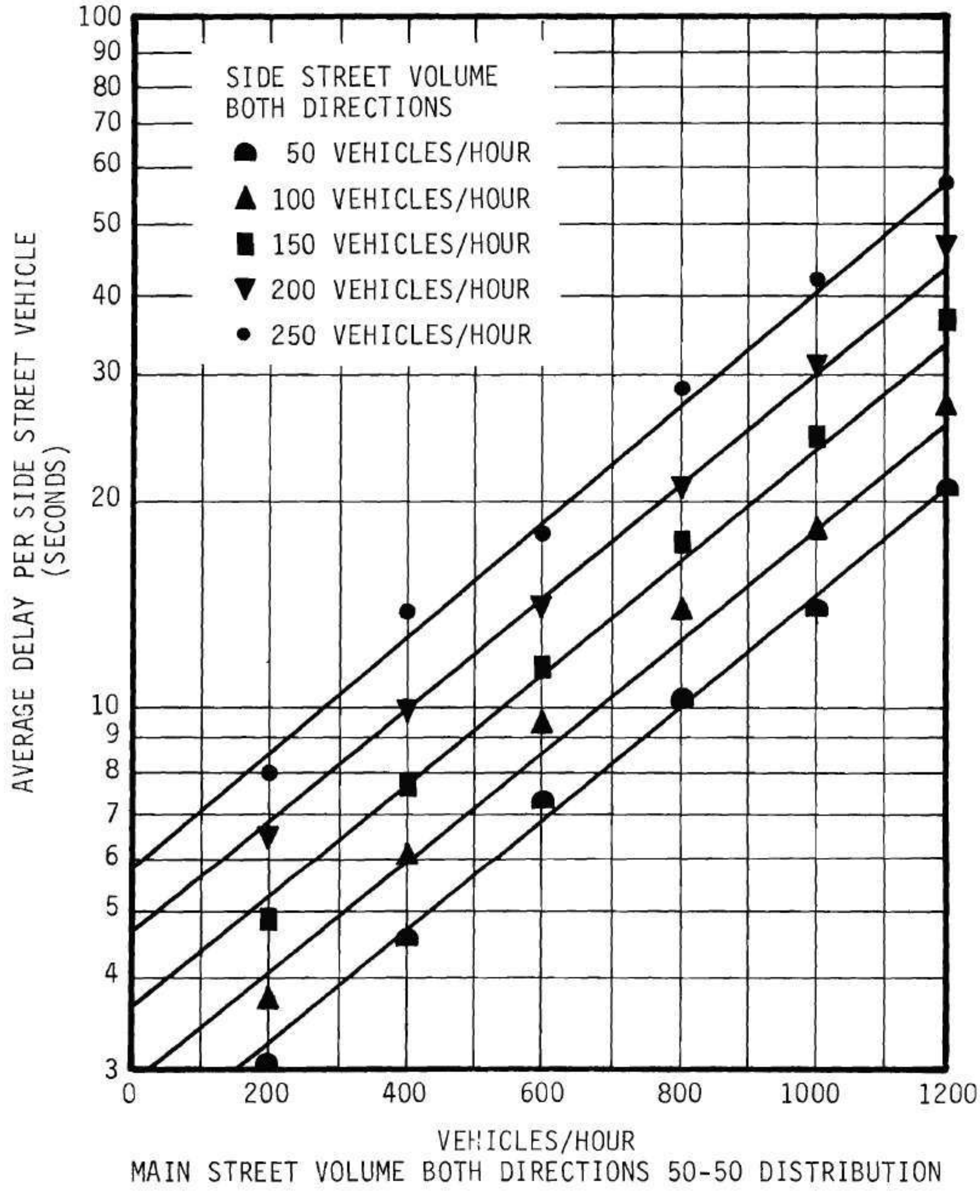


Figure 29. The Effect of Main Street Volume on Average Delay Per Side Street Vehicle at Thirty Percent Right Turns.

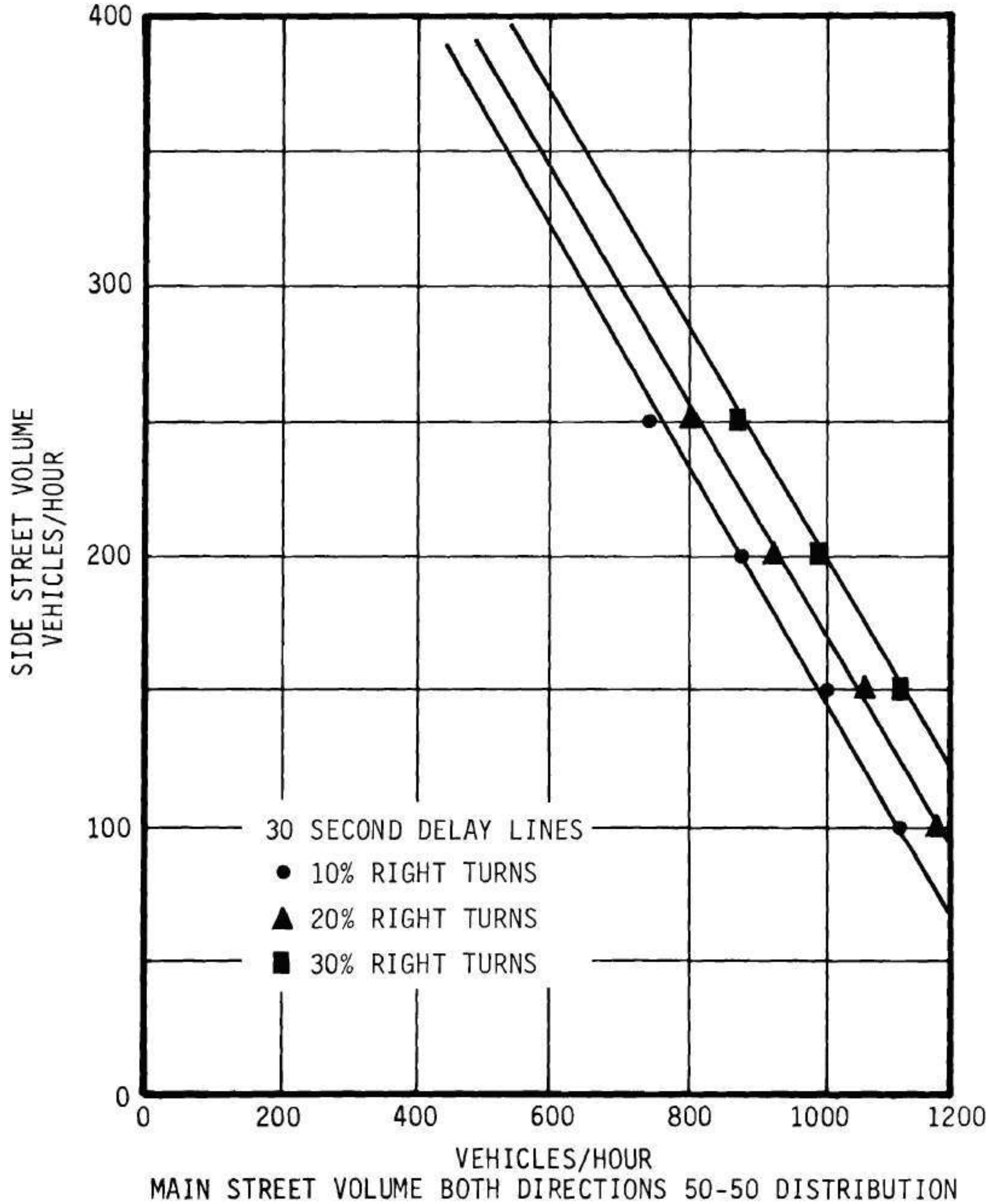


Figure 30. The Relationship of Main Street and Side Street Volumes for Average Delay of Thirty Seconds for Various Right Turn Percentages.

20, and 30 per cent of right turns.

Figure 31 indicates that results of this research are generally consistent with the results of Kell (10) and Lewis (11). Any differences may be attributed to:

1. Use of different arrival model
2. Use of different acceptance model
3. Directional distribution of main street volume
4. Manner in which vehicles were served.

It is further noted that Lewis (11) used a critical lag of 4.8 and 5.8 seconds. For the intersections studied in this research, the critical lag was 8.6 seconds as shown by Figure 32. This high critical lag was probably due to:

1. Selection of rural and residential intersections
2. Higher main street speeds
3. Lower volumes than in urban areas
4. Driver differences.

Figure 33 compares lines of 30-second delay for Lewis' research with the results of this study.

Figures 34-36 show the effects of main street and side street volumes on average side street delay. Lines of equal average delay of 30, 45, and 60 seconds are shown for different percentages of right turn movements. These results should only be interpreted as indicative of probable relationships since few data points were available at high volume levels. However, when used in conjunction with other traffic factors such as speed, accident experience, and pedestrian volumes, one could use data such as this in arriving at

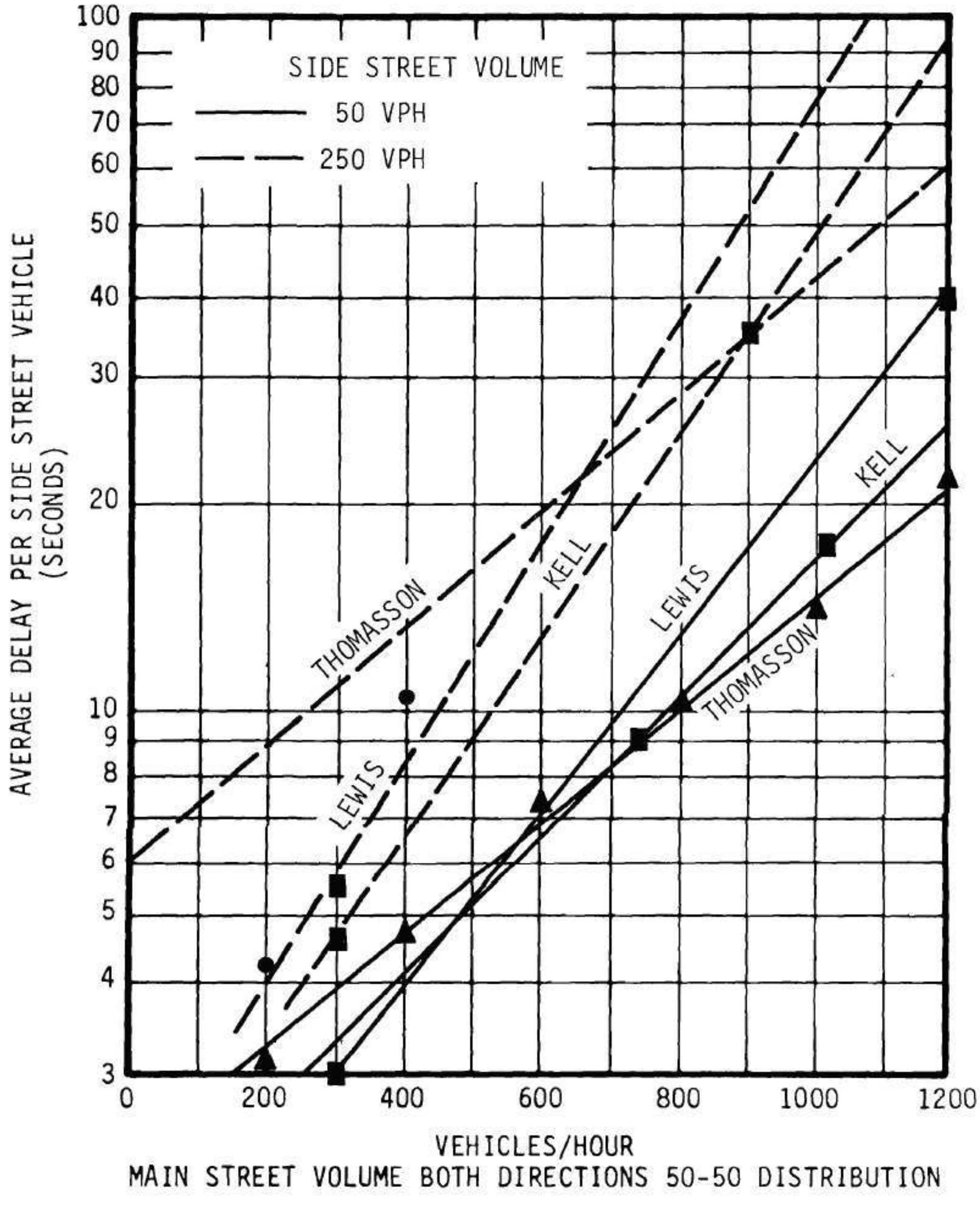


Figure 31. A Comparison of the Effect of Main Street Volumes on Average Delay, as Determined by Various Researchers.

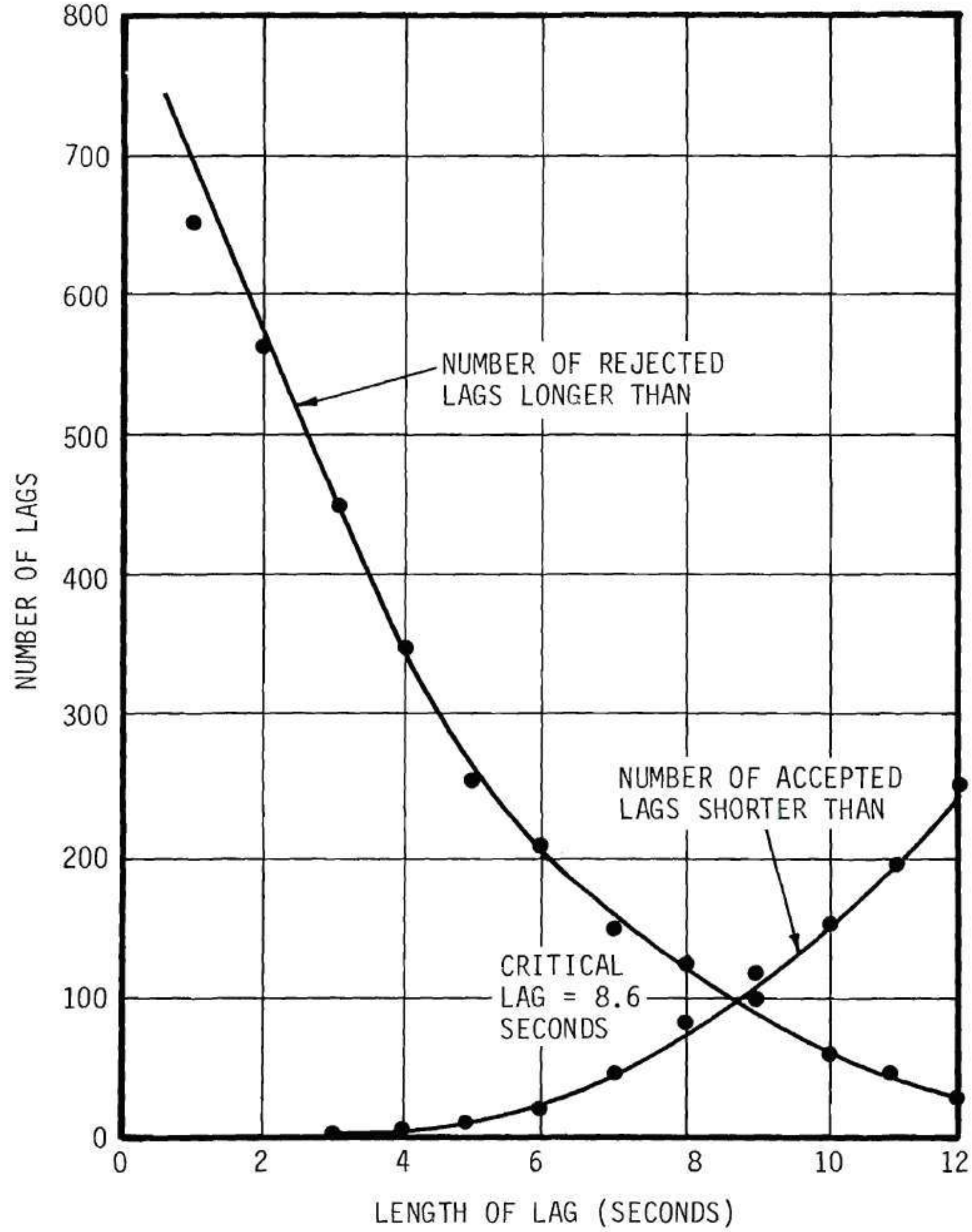


Figure 32. Cumulative Distribution of Accepted and Rejected Lags for All Intersections.

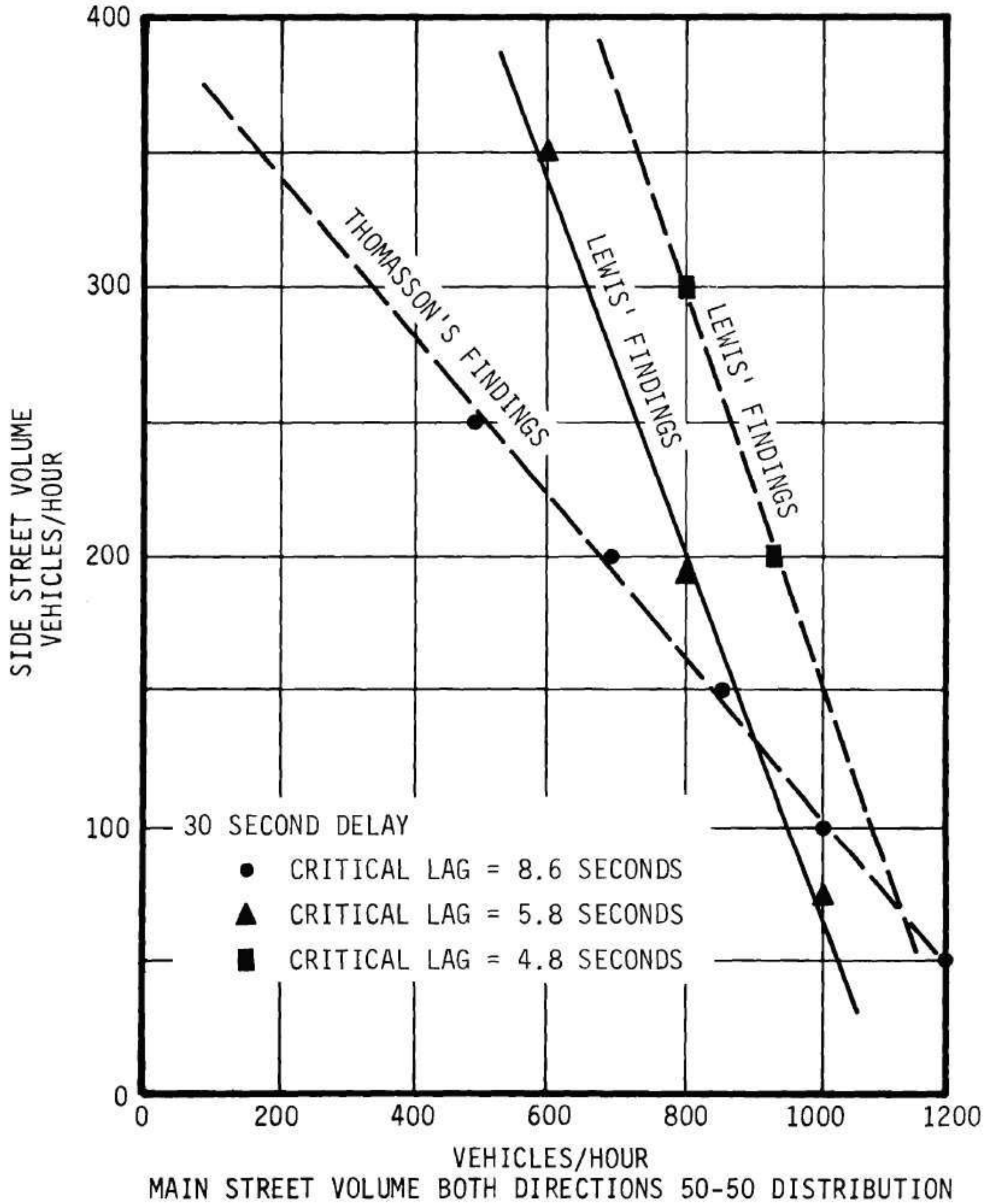


Figure 33. The Relationship of Main Street and Side Street Volumes for Average Delay of Thirty Seconds at Various Critical Lags.

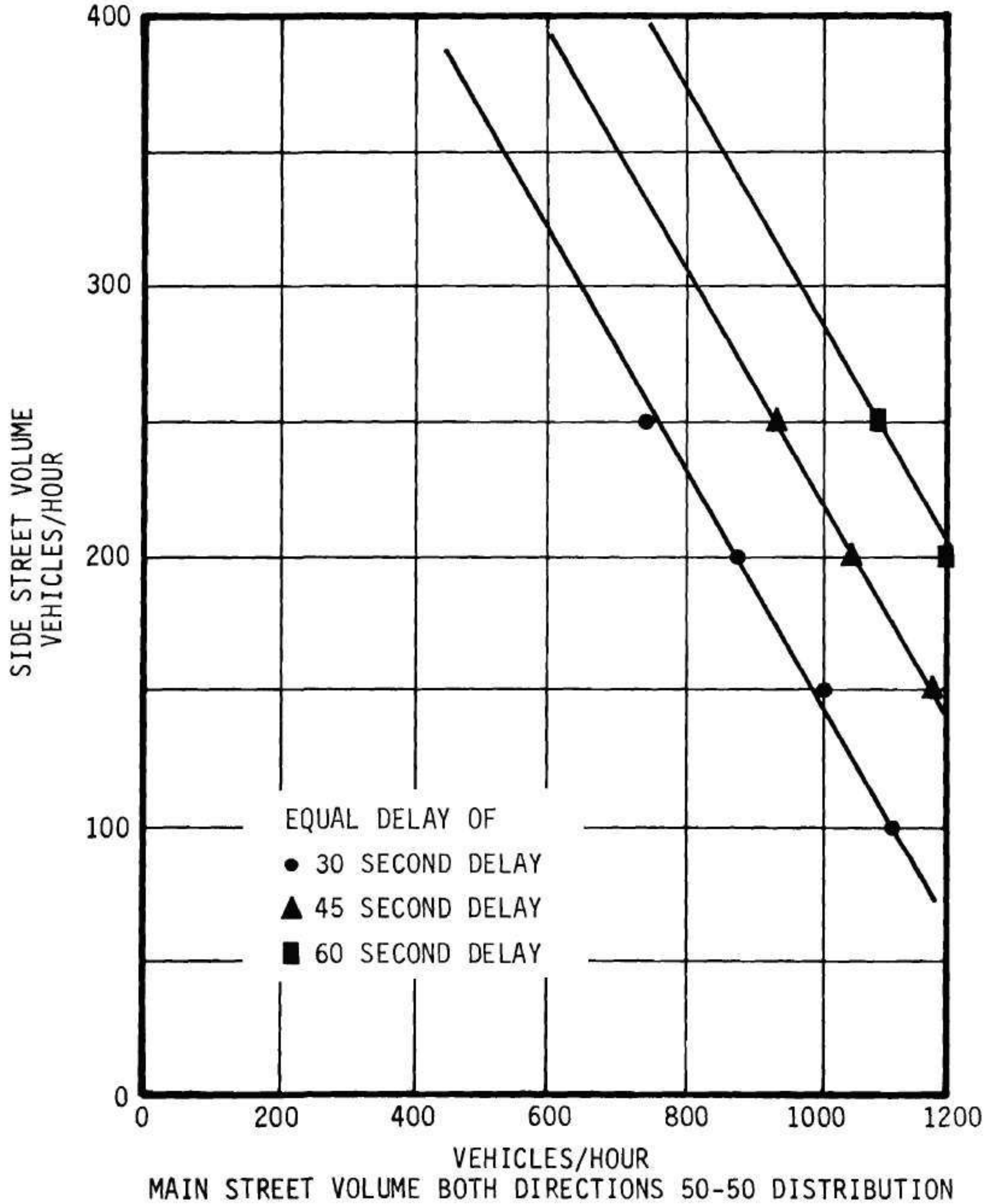


Figure 34. Equal Average Delay Lines for Ten Percent Right Turns.

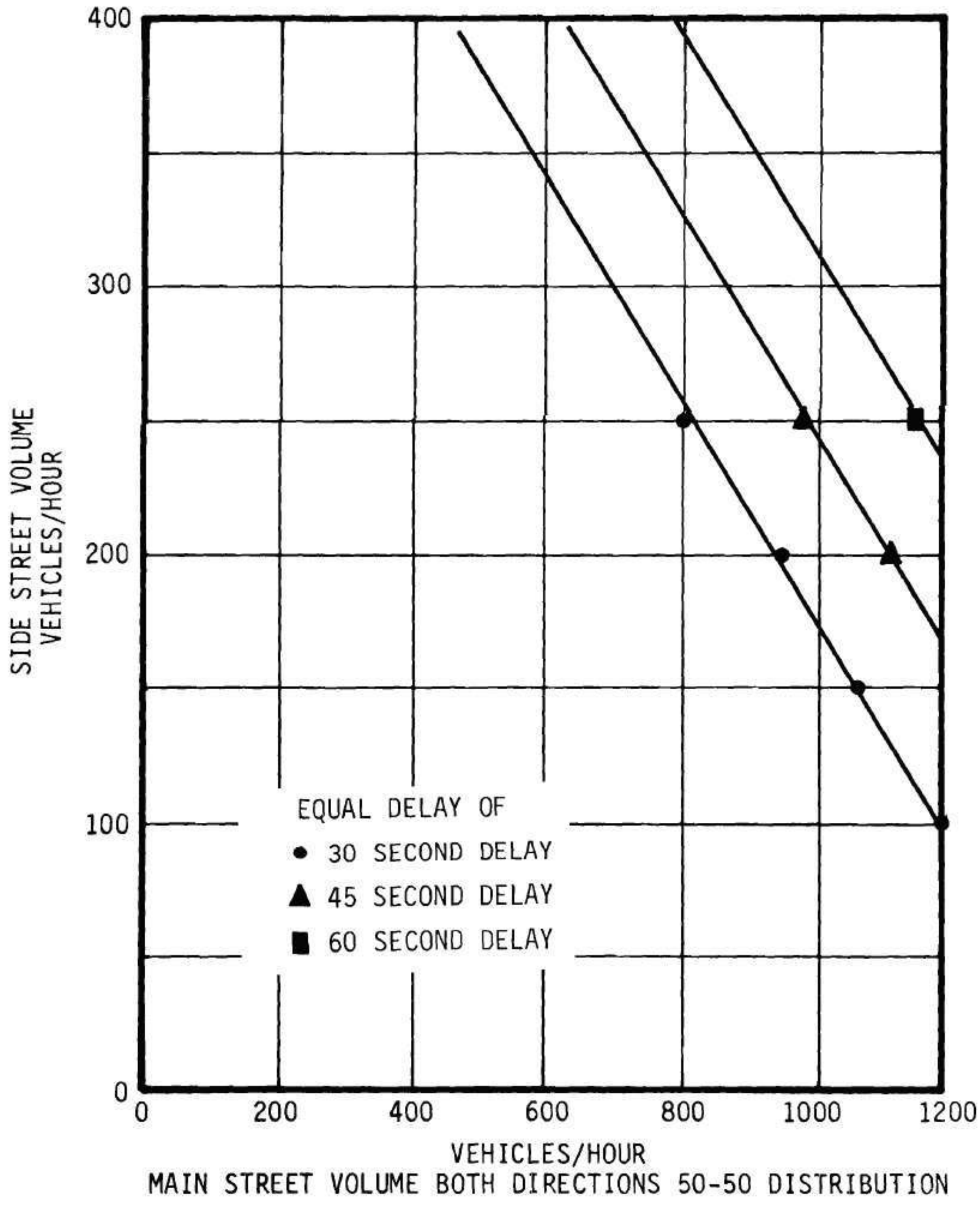


Figure 35. Equal Average Delay Lines for Twenty Percent Right Turns.

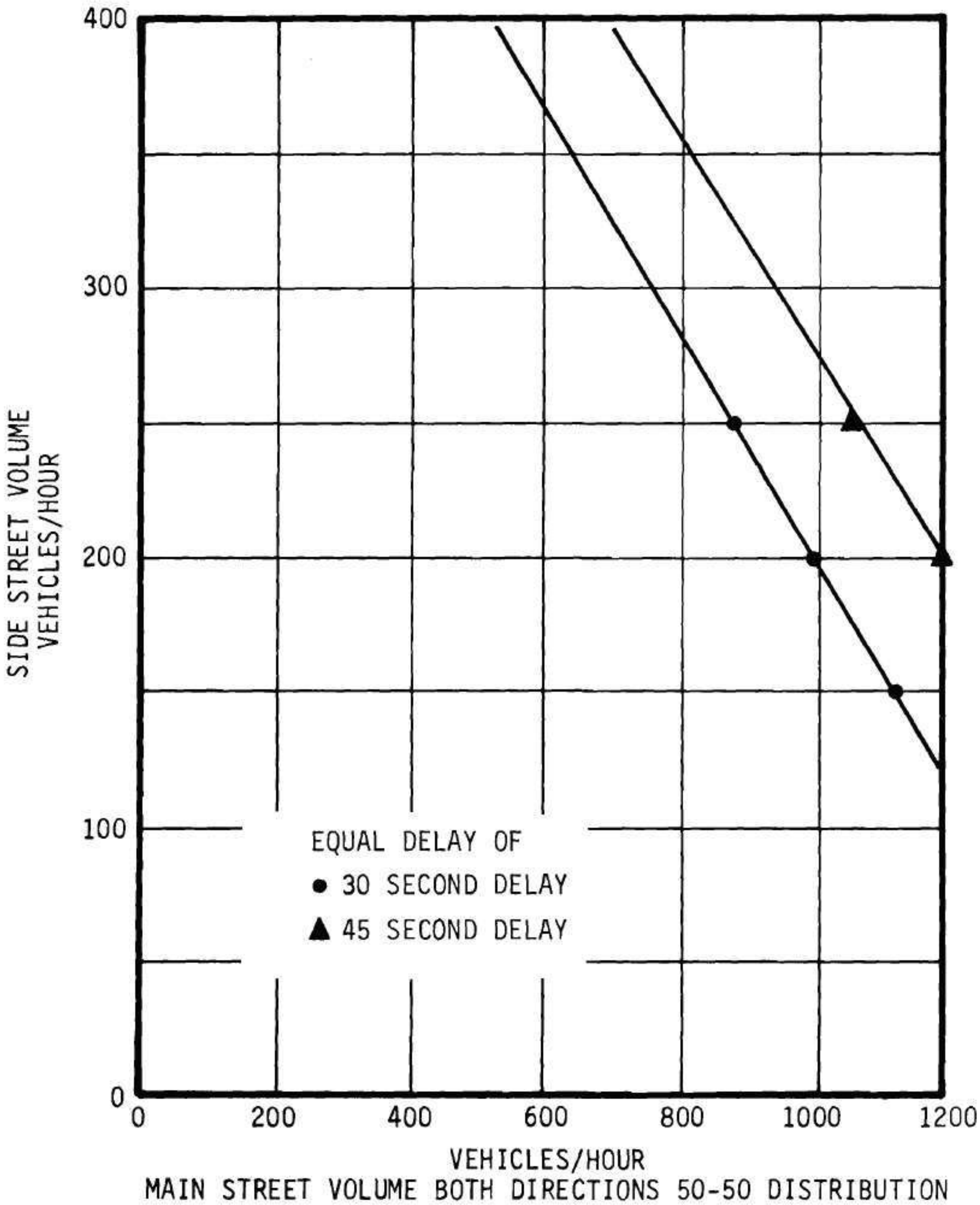


Figure 36. Equal Average Delay Lines for Thirty Percent Right Turns.

volume warrants for different signals. By assuming some tolerable average delay per side street vehicle, the upper limits of side street and main street volumes for stop sign control could be read from the curves.

Due to the nature of the output, the problem of determining average queue lengths proved to be a formidable one. It was possible to determine queue length relationships only at low volumes. These relationships are shown in Figure 37 and Table 2. As expected, the average queue length increased with increases in main street volume. The rate of increase became more pronounced as side street volumes were increased.

Table 2

Average queue length for various side street and main street volumes -- 30% right turns.

Side Street Volumes Vehicles/hour	Main Street Volume, UPH 200	400	600	800
50	1.07	1.13	1.19	1.26
100	1.08	1.16	1.24	1.36
150	1.10	1.20	1.32	1.38

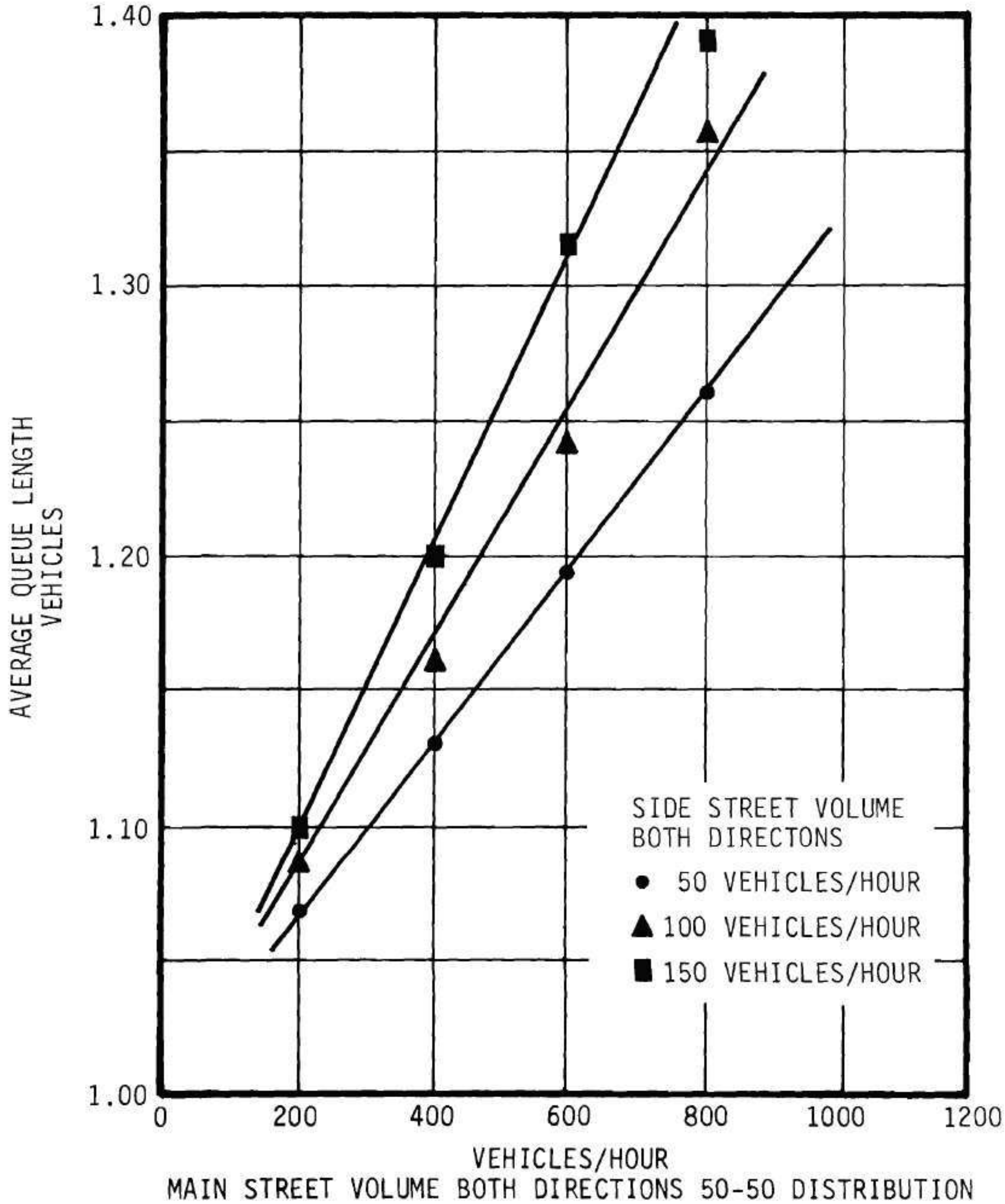


Figure 37. The Effect of Main Street Volume on Average Queue Length at Various Side Street Volumes and Thirty Percent Right Turns.

CHAPTER IV

CONCLUSIONS

1. Simulation can be an effective means of studying intersections under a wide variety of traffic conditions. It is a useful alternative to empirical studies which tend to be costly and time-consuming.

2. Field observations made in this research corroborated the findings of earlier researchers that the relationship between the logarithmic transform of lags and gaps and the probability of acceptance follows a cumulative normal distribution curve.

3. The lag and gap acceptance distributions for drivers making left turns were strikingly similar to those for drivers making straight movements. Results of this research failed to show any important differences between these distributions.

4. Drivers making right turn movements tended to be more likely to accept lags and gaps of a given size than drivers making straight or left movements.

5. The time a driver hesitates before beginning to move into the intersection upon the availability of an acceptable gap or lag was termed "starting time" in this research. It was found that starting times could be modeled by the normal distribution.

6. Service times, the times vehicles remained in the intersection area, were found to be normally distributed. Mean service time for straight movements was slightly larger than that for right turns, but slightly smaller than that for left turns.

7. The results of expermients conducted by use of the simulation model were not surprising. The major findings of the simulation runs are as follows:

a. Average delay per side street vehicle increased with increases in side street and main street volumes. At all levels of side street volumes simulated, average delay appeared to increase logarithmically with increases in main street volumes.

b. Simulation runs indicated that average delay per side street vehicle increases with increases in the percentages of the more complex left and straight movements.

c. Because the extraction of average queue lengths data from the output was tedious and difficult, only a limited study of this parameter was made. This study indicated that average side street queues increase with increases in main street volumes. As expected, this rate of increase was greater at high side street volumes.

CHAPTER V

RECOMMENDATIONS FOR FUTURE STUDY

The limited scope and resources for this research precluded the study of many relationships of interest and limited the refinement of the simulation model. The following suggestions are made as possible areas of profitable future research:

1. A study of main street headway distributions and the influence of these distributions on side street delays.

2. A study of delays to vehicles at side street approaches which intersect a main street with four or more lanes.

3. An investigation of the effect of cross street movements on the size of main street gaps.

4. Development of a refined simulation model which permits turning movements of main street vehicles.

APPENDIX

Table 3. Lag Acceptance Frequency Table--Right Turns

Time Upper Limit	Right Turns - Frequency For Lags							
	N. Highland		Covington		Moore's Mill		Combined	
	Accepted	Rejected	Accepted	Rejected	Accepted	Rejected	Accepted	Rejected
1.0	--------	21	--------	3	--------	1	--------	25
2.0	--------	12	--------	2	--------	5	--------	19
3.0	1	17	--------	2	--------	3	1	22
4.0	1	7	--------	4	--------	2	1	13
5.0	3	3	--------	2	--------	1	3	6
6.0	5	4	--------	--------	2	--------	7	4
7.0	4	1	--------	1	1	--------	5	2
8.0	6	5	1	--------	3	1	10	6
9.0	3	1	1	1	2	--------	6	2
10.0	3	1	2	1	3	2	8	4
11.0	5	1	3	1	1	--------	9	2
12.0	4	1	3	--------	1	1	8	2
13.0	4	--------	4	1	1	1	9	2

Table 4. Lag Acceptance Frequency Table -- Left Turns

Left Turn - Frequency for Lags								
Time Upper Limit	N. Highland		Covington		Moore's Mill		Combined	
	Accepted	Rejected	Accepted	Rejected	Accepted	Rejected	Accepted	Rejected
1.0	-	21	-	5	-	8	-	34
2.0	-	21	-	4	-	22	-	47
3.0	-	27	-	3	-	19	-	49
4.0	2	14	-	2	-	14	2	30
5.0	1	11	-	4	-	12	1	27
6.0	3	8	-	2	-	13	3	23
7.0	9	10	-	1	2	10	11	21
8.0	5	3	-	-	2	7	7	10
9.0	8	3	1	4	4	9	13	16
10.0	6	6	1	1	5	6	12	13
11.0	9	2	3	1	7	7	19	10
12.0	6	1	2	1	9	4	17	6
13.0	5	1	2	1	12	2	19	4

Table 5. Lag Acceptance Frequency Table -- Straight Movements

Straight - Frequency for Lags

Time Upper Limit	N. Highland Accepted	N. Highland Rejected	Covington Accepted	Covington Rejected	Moore's Mill Accepted	Moore's Mill Rejected	Combined Accepted	Combined Rejected
1.0	-	20	-	16	-	4	-	40
2.0	-	24	-	14	-	12	-	50
3.0	-	19	-	9	-	9	-	37
4.0	-	17	1	11	-	7	1	35
5.0	2	12	2	5	-	4	4	21
6.0	3	6	2	14	1	2	6	22
7.0	6	3	2	6	3	1	11	10
8.0	4	2	4	10	2	2	10	14
9.0	3	5	3	7	4	1	10	13
10.0	5	2	8	4	5	1	18	7
11.0	2	4	10	2	7	1	19	7
12.0	3	2	11	2	4	-	18	4
13.0	-	-	6	5	5	1	11	6

Table 6. Gap Acceptance Frequency Table -- Right Turns

Right Turns - Frequency Table -- Right Turns

Time Upper Limit	N. Highland Accepted	N. Highland Rejected	Covington Accepted	Covington Rejected	Moore's Mill Accepted	Moore's Mill Rejected	Combined Accepted	Combined Rejected
1.0	-	3	-	3	-	1	-	7
2.0	-	46	-	4	-	4	-	54
3.0	-	38	-	2	-	2	-	42
4.0	1	19	-	3	-	-	1	22
5.0	1	11	-	1	-	-	1	12
6.0	4	5	-	1	1	1	5	8
7.0	4	3	-	-	-	1	4	3
8.0	4	2	1	-	1	-	6	2
9.0	7	-	-	1	2	2	9	3
10.0	3	-	1	1	-	-	4	1
11.0	6	1	-	-	1	1	7	2
12.0	-	1	1	-	3	1	4	2
13.0	4	1	-	-	4	1	8	2

Table 7. Gap Acceptance Frequency Table -- Left Turns

Time Upper Limit	N. Highland		Covington		Moore's Mill		Combined	
	Left Turns - Frequency for Gaps							
	Accepted	Rejected	Accepted	Rejected	Accepted	Rejected	Accepted	Rejected
1.0	-	6	-	-	-	14	-	20
2.0	-	113	-	4	-	93	-	210
3.0	-	151	-	4	-	87	-	242
4.0	3	72	-	1	-	35	3	108
5.0	3	35	-	1	1	24	4	60
6.0	8	15	-	1	4	19	12	35
7.0	7	19	-	-	7	14	14	33
8.0	8	12	-	-	6	11	14	23
9.0	7	8	1	-	9	9	17	17
10.0	8	6	1	-	12	7	21	13
11.0	8	4	3	1	10	6	21	11
12.0	10	3	3	-	9	4	22	7
13.0	10	2	3	1	8	1	31	4

Table 8. Gap Acceptance Frequency Table -- Straight Movements

Straight - Frequency for Gaps

Time Upper Limit	N. Highland		Covington		Moore's Mill		Combined	
	Accepted	Rejected	Accepted	Rejected	Accepted	Rejected	Accepted	Rejected
1.0	-	9	-	4	-	1	-	14
2.0	-	108	-	29	-	21	-	158
3.0	1	142	-	23	-	17	1	182
4.0	1	82	-	4	-	19	1	105
5.0	3	40	1	1	-	12	4	53
6.0	10	38	-	3	1	10	11	51
7.0	7	12	1	1	-	11	8	24
8.0	5	9	3	1	3	9	11	19
9.0	8	5	2	1	2	7	12	13
10.0	7	4	-	1	3	7	10	12
11.0	11	2	4	-	5	5	20	7
12.0	15	3	3	-	9	2	27	5
13.0	6	1	3	1	3	1	12	3

Table 9. Combined Lag Acceptance Percentages for all Three Intersections -- Left Turns

Time	Number Accepted	Number Rejected	Total	Percent Acceptance
1.0	-	34	34	0
2.0	-	47	47	0
3.0	-	49	49	0
4.0	2	30	32	6.3
5.0	1	27	28	3.6
6.0	3	23	26	11.5
7.0	11	21	32	34.4
8.0	7	10	17	41.2
9.0	13	16	29	44.8
10.0	12	13	25	48.0
11.0	19	10	29	65.5
12.0	17	6	23	73.9
13.0	19	4	23	82.6

Table 10. Combined Lag Acceptance Percentages for All Three Intersections -- Right Turns

Time	Number Accepted	Number Rejected	Total	Percent Acceptance
1.0	--	25	25	0
2.0	-	19	19	0
3.0	1	22	23	4.3
4.0	1	13	14	7.1
5.0	3	6	9	33.3
6.0	7	4	11	63.6
7.0	5	2	7	71.4
8.0	10	6	16	62.5
9.0	6	2	8	75.0
10.0	8	4	12	66.7
11.0	9	2	11	81.8
12.0	8	2	10	80.0
13.0	9	2	11	81.8

Table 11. Combined Lag Acceptance Percentages for All Three Intersections -- Straight Movements

Time	Number Accepted	Number Rejected	Total	Percent Acceptance
1.0	-	40	40	0
2.0	-	50	50	0
3.0	-	37	37	0
4.0	1	35	36	2.8
5.0	4	21	25	8.0
6.0	6	22	28	21.4
7.0	11	10	21	52.4
8.0	10	14	24	41.7
9.0	10	13	23	43.5
10.0	18	7	25	72.0
11.0	19	7	26	73.1
12.0	18	4	22	81.8
13.0	11	6	17	64.7

Table 12. Combined Gap Acceptance Percentages for All Three Intersections -- Left Turns

Time	Number Accepted	Number Rejected	Total	Percent Acceptance
1.0	-	20	20	0
2.0	-	210	210	0
3.0	-	242	242	0
4.0	3	108	111	2.7
5.0	4	60	64	6.3
6.0	12	35	47	25.6
7.0	14	33	47	29.8
8.0	14	23	37	37.8
9.0	17	17	34	50.0
10.0	21	13	34	61.8
11.0	21	11	32	65.6
12.0	22	7	29	75.9
13.0	31	4	35	88.6

Table 13. Combined Gap Acceptance Percentages for All Three Intersections -- Right Turns

Time	Number Accepted	Number Rejected	Total	Percent Acceptance
1.0	-	7	7	0
2.0	-	54	54	0
3.0	-	42	42	0
4.0	1	22	23	4.3
5.0	1	12	13	7.7
6.0	5	8	13	38.5
7.0	4	3	7	57.1
8.0	6	2	8	75.0
9.0	9	3	12	75.0
10.0	4	1	5	80.0
11.0	7	2	9	77.8
12.0	4	2	6	66.7
13.0	8	2	10	80.0

Table 14. Combined Gap Acceptance Percentages for All Three Intersections -- Straight Movement

Time	Number Accepted	Number Rejected	Total	Percent Acceptance
1.0	-	14	14	0
2.0	-	158	158	0
3.0	1	182	183	0.5
4.0	1	105	106	0.9
5.0	4	53	57	7.0
6.0	11	51	62	17.7
7.0	8	24	32	25.0
8.0	11	19	30	36.7
9.0	12	13	25	48.0
10.0	10	12	22	45.5
11.0	20	7	27	74.1
12.0	27	5	32	84.4
13.0	12	3	15	80.0

Table 15. Average Delay Per Side Street Vehicle -- 10% Right Turns.

Main Street Volume, VPH	Side Street Volume, Vehicles/Hour 50	100	150	200	250
200	4.1	5.0	6.9	8.3	9.7
400	5.3	7.6	8.7	11.2	15.4
600	7.9	9.9	12.2	17.9	22.1
800	11.3	16.2	20.8	26.7	34.5
1000	18.2	14.7	30.0	39.8	51.7
1200	28.1	36.0	47.9	59.1	78.0

Table 16. Average Delay Per Side Street Vehicle -- 20% Right Turns

Main Street Volume, VPH	Side Street Volume, Vehicles/Hour 50	100	150	200	250
200	2.4	3.9	6.3	8.8	9.8
400	5.7	7.9	9.2	11.2	14.3
600	8.1	9.4	12.1	17.2	21.0
800	11.0	14.8	19.2	23.7	31.5
1000	15.8	21.3	29.2	37.0	47.3
1200	23.1	32.2	42.0	51.8	65.6

Table 17. Average Delay Per Side Street Vehicle -- 30% Right Turns.

Main Street Volume, VPH	Side Street Volume, Vehicles/Hour				
	50	100	150	200	250
200	2.2	3.7	6.1	8.0	9.1
400	4.6	7.2	8.1	10.0	15.1
600	8.2	9.8	12.3	16.2	18.8
800	10.0	15.3	19.2	21.7	28.1
1000	15.0	19.4	25.3	31.1	42.3
1200	21.4	28.1	37.2	47.4	58.3

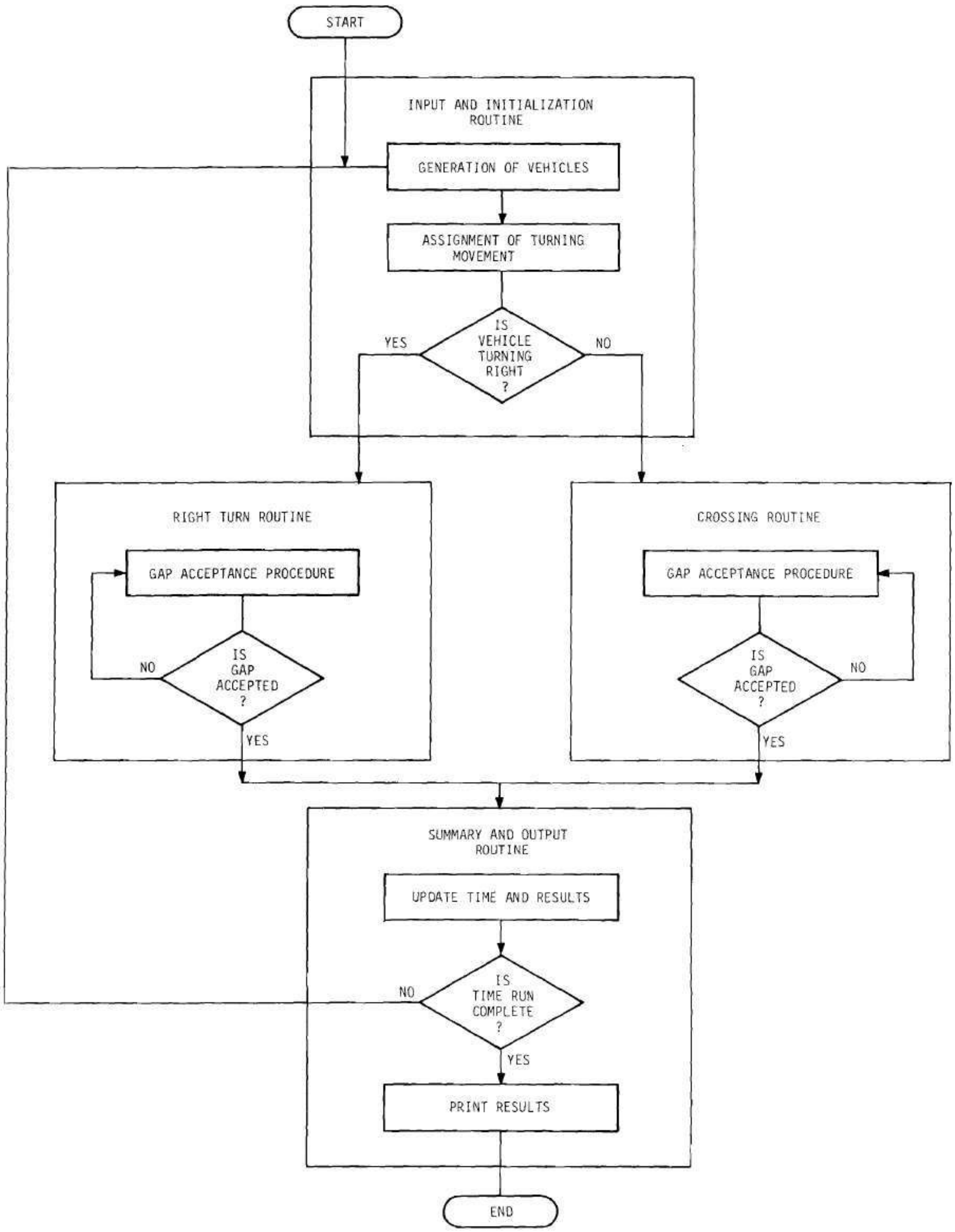


Figure 38a. Detailed Flow Chart for Simulation Model, Appendix.

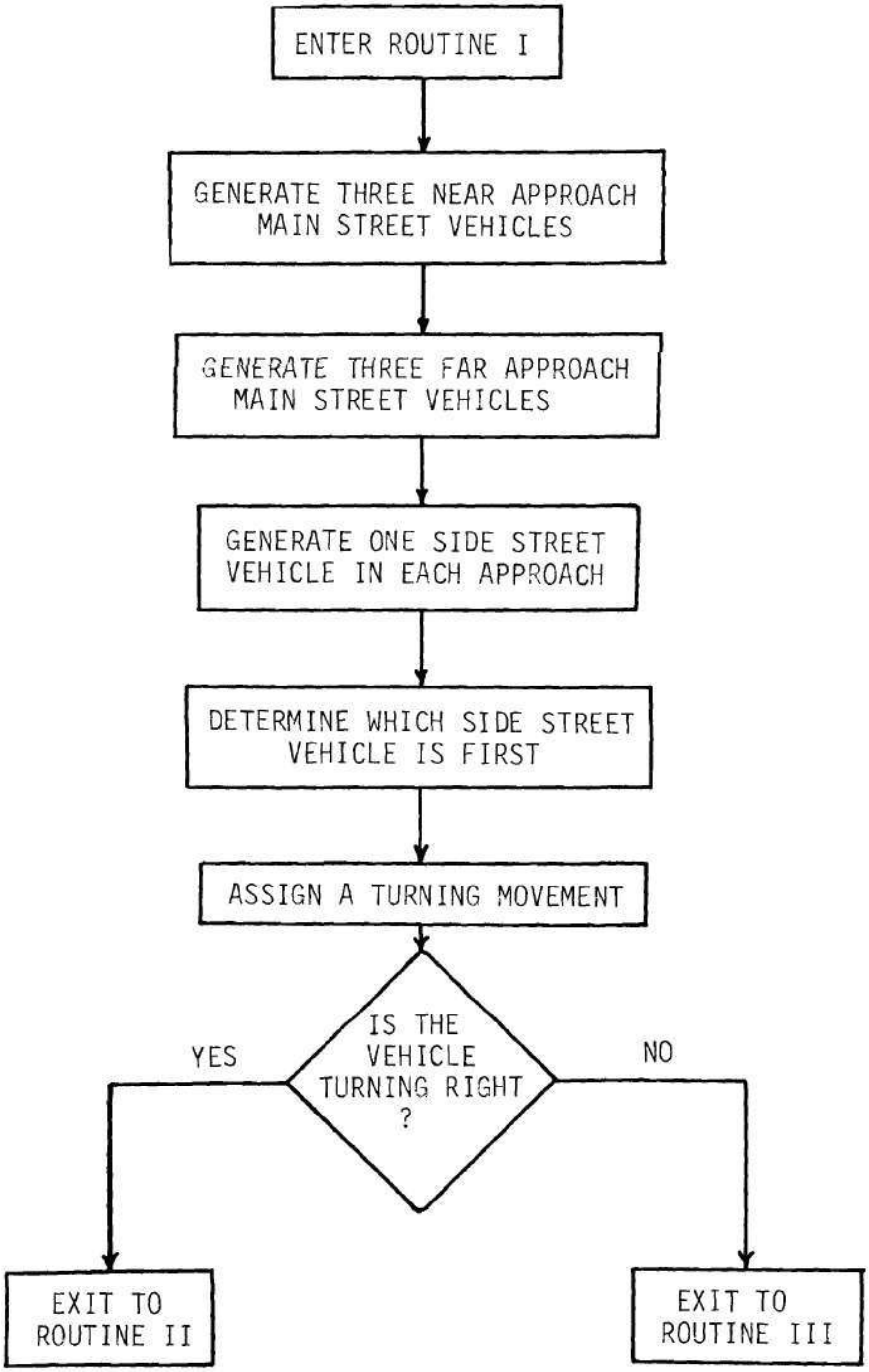


Figure 38b. Detailed Flow Chart for Simulation Model (Cont.).

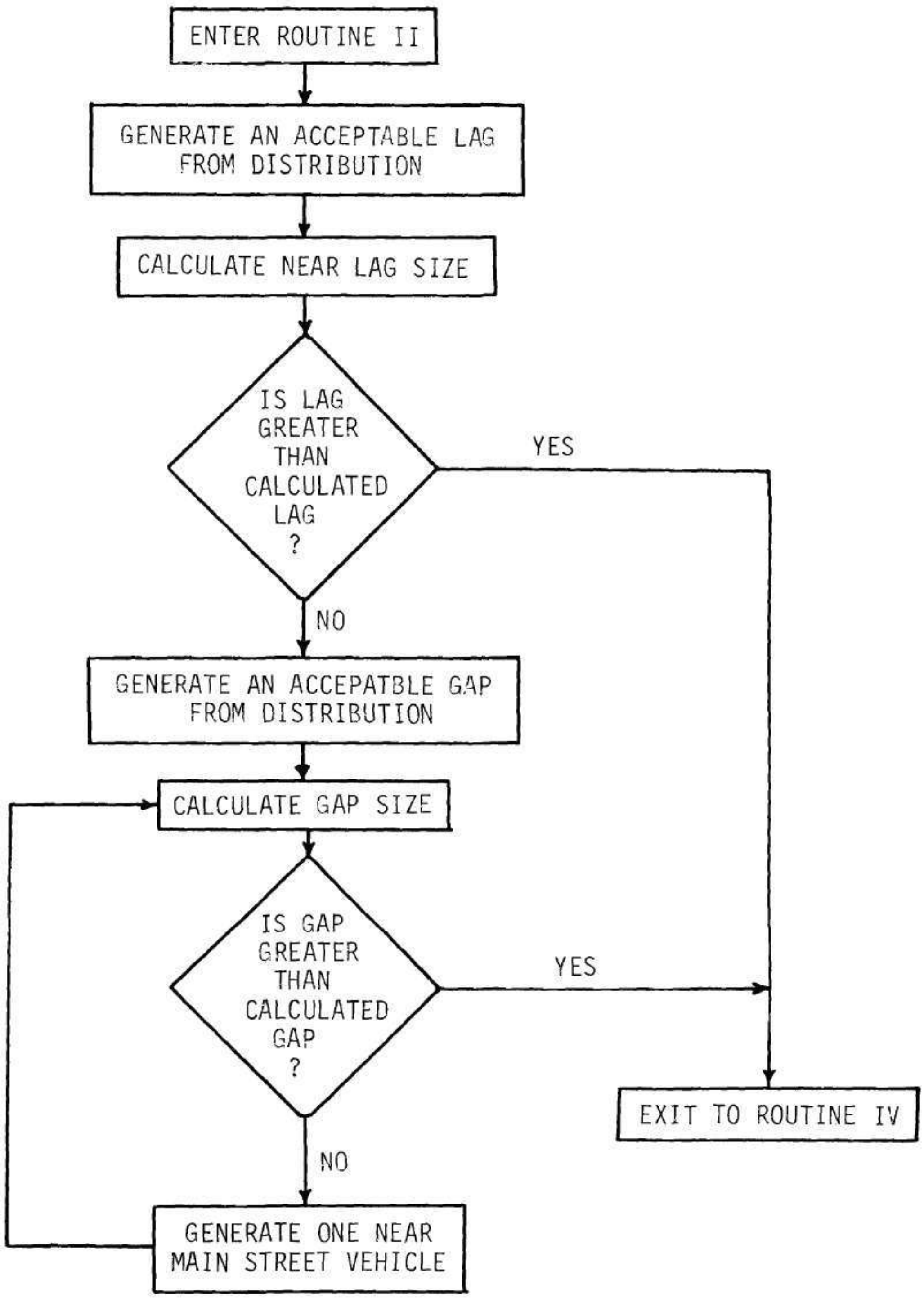


Figure 38c. Detailed Flow Chart for Simulation Model (Cont.).

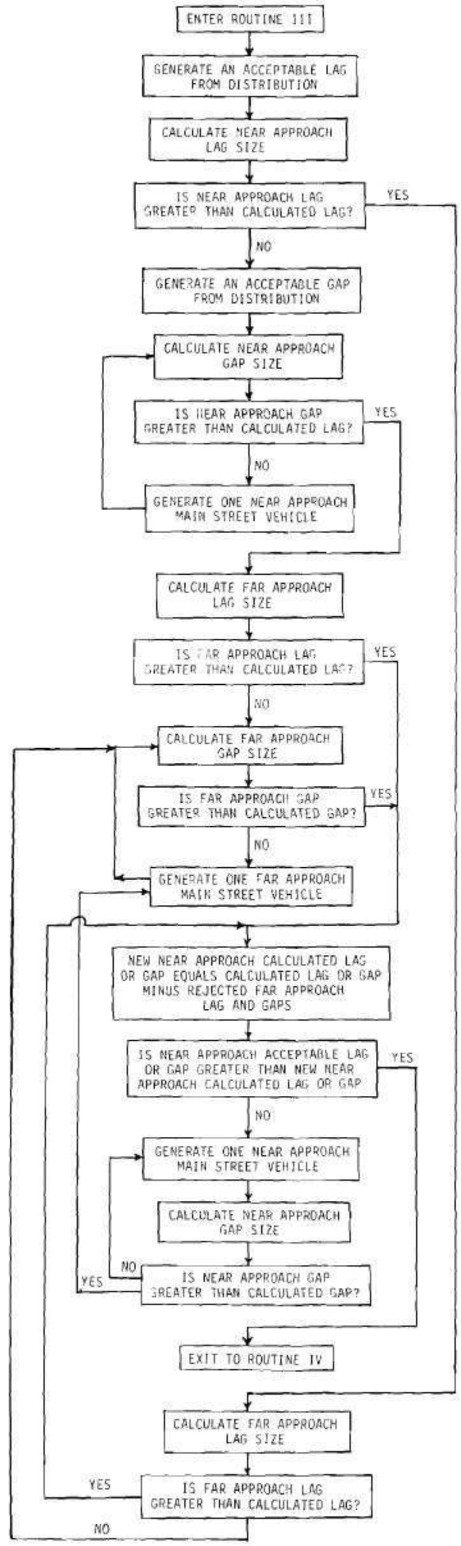


Figure 38d. Detailed Flow Chart for Simulation Model (Cont.).

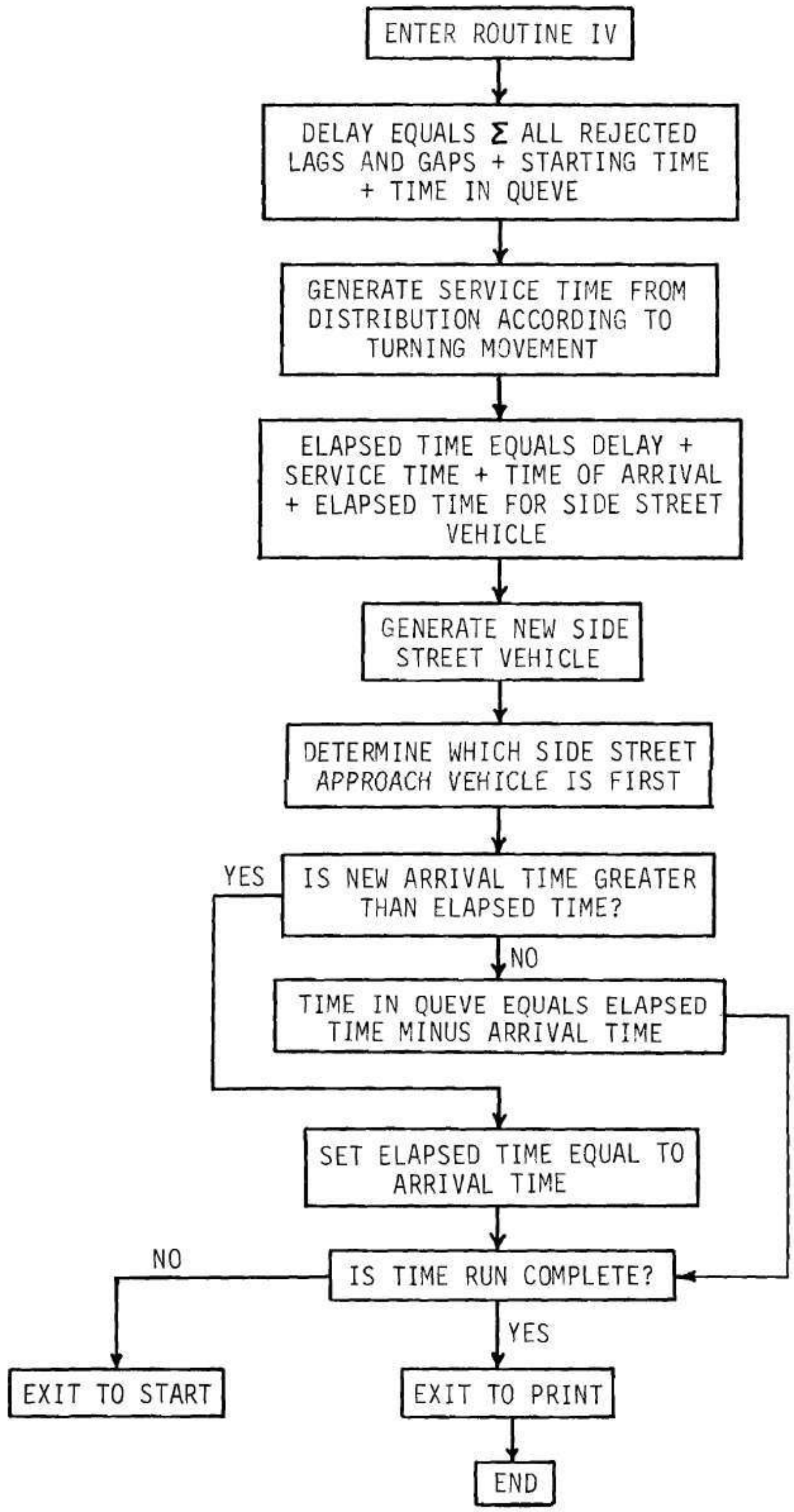


Figure 38e. Detailed Flow Chart for Simulation Model (Cont.).

LIST OF REFERENCES

1. Raff, M. S., and Hart, J. W. A Volume Warrant for Urban Stop Signs. Eno Foundation for Highway Traffic Control, Saugatuck, Conn., 1950.

2. Bissell, H. H. "Traffic Gap Acceptance from a Stop Sign". M. S. Thesis, University of California, May 1960

3. Wagner, F. A. "An Evaluation of Fundamental Driver Decisions and Reactions at an Intersection".

4. Snell, J. E., "Simulation of Highway Intersection Performance-A Simplified Example". November, 1963. (mimeo.)

5. Kell, J. H., "Analyzing Vehicular Delay at Intersections Through Simulation", Highway Research Board Bulletin 356, pp. 28-39, 1962.

6. Gerlough, D. L., "Simulation of Freeway Traffic Flow by an Electronic Computer". Proceedings, Highway Research Board, Volume 35, pp 543-547, 1956.

7. Lewis, R. M., and Michael, H. L. "Simulation of Traffic Flow to Obtain Volume Warrants For Intersection Control". Highway Research Record Number 15, pp 1-43, 1963.

8. Ruiter, E. R. and Shuldiner, P. W. "Operating Cost at Intersections Obtained From the Simulation of Traffic Flow". U. S. Department of Commerce, Bureau of Public Roads, (1961).

9. "Manual on Uniform Traffic Control Devices for Streets and Highways". U. S. Department of Commerce, Bureau of Public Roads,(1961)

10. Kell, J. H., "Intersection Delay Obtained by Simulating Traffic on a Computer". Highway Research Record Number 15, pp 73-97, 1963.

11. Lewis, R. M. "The Simulation of Traffic Flow to Obtain Volume Warrants for Intersection Control". Ph. D. thesis, Purdue University, September, 1962.

OTHER REFERENCES

Bleyl, R. L. "Simulation of Traffic Flow to Compare Regular and Flashing Traffic Signal Operation". Proceedings, 34th Annual Meeting, Institute of Traffic Engineers pp. 153-161, 1964.

Kell, J. H., "A Theory of Traffic Flow on Urban Streets." Proceedings, 13th Annual Western Section Meeting. Institute of Traffic Engineers. pp. 71-107, 1963.

Kell, J. H., "Results of Computer Simulation Studies as Related to Traffic Signal Operation". Proceedings, 33th Annual Meeting, Institute of Traffic Engineers pp 71-107, 1963.

Rhee, S. Y., "The Urban Traffic Control Simulaton". M. S. thesis, Case Institute of Technology.